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Photovoltaics: Environmental, Health and Safety Issues and Perspectives†

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The photovoltaic (PV) industry must continue its pro-active approach to prevent accidents and environmental damage, and to sustain PV's inherent environmental, health, and safety (EHS) advantages. This paper presents an overview of EHS issues related to current and emerging PV technologies and gives examples of this pro-active approach. We summarize the hazards related to potential accidental releases of toxic or flammable gases used in photovoltaic cell production, and strategies for reducing such risks (e.g., choosing material and process options which inherently have small risks, and preventing accident-initiating events). Other issues discussed herein include reducing the use of toxic or carcinogenic materials in powder form, managing liquid hazardous waste, and recycling solid waste and spent modules. As the PV industry approaches these issues and mitigation strategies in a vigilant, systematic way, the risk to the industry, the workers, and the public will become minimal. An example is also discussed of environmental benefits from a large scale PV implementation, that is the potential of PV in reducing CO_2 emissions. Published in 2000 by John Wiley & Sons, Ltd.

INTRODUCTION

The photovoltaic technologies have distinct environmental advantages over conventional technologies for electricity generation. The operation of photovoltaic systems does not produce any noise, toxic-gas emissions, nor greenhouse gases. Photovoltaic energy not only can help meet the growing worldwide demand for electricity, but it can do so without incurring the high economic and environmental costs of installing power lines or burning fossil fuels. Relative to burning coal, every gigawatt-hour of electricity generated by photovoltaics would prevent the emission of about 10 tons of SO_2, 4 tons of NO_x, 0·7 tons of particulates (including 1 kg of Cd and 120 kg of As), and up to 1000 tons of CO_2. PV's land-use requirements are similar to those for coal production and combustion. PV's material requirements are extremely low (e.g., 1 MWh/g semiconductor material); they are about the same order as those of a breeder reactor with 50% fuel recycling (e.g., 4 MWh/g uranium);[1] further the semiconductor materials used in solar cells do not pose the environmental problems related to uranium and fission by-products.

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As with any energy source or product, there are EHS hazards associated with the manufacture, use, and disposal of solar cells. Although the PV industry uses far smaller amounts of toxic and flammable substances than many other industries, its use of hazardous chemicals can present occupational and environmental hazards. Addressing EHS concerns is the focus of numerous studies at Brookhaven National Laboratory, under the auspices of the US Department of Energy's National Photovoltaic Program.[2–5] In Europe, research on environmental aspects of PV is supported by the International Energy Agency (IEA)[6] and the Netherlands Organization for Energy and the Environment (Novem).[6,7]

The PV industry exercises continuing vigilance to minimize the risks of hazardous substances, and has adopted a pro-active, long-term environmental strategy to prevent potential environmental damage by products and processes. Successful commercialization of new photovoltaic technologies will require continuous attention to EHS issues related to the sources, processing, usage, and end-of-product-life disposal. This paper focuses on such issues in the manufacture of crystalline-Si, amorphous-Si, $CuInSe_2$ and CdTe solar cells.

HAZARDS IN PV MANUFACTURE

Photovoltaic cell fabrication facilities may adversely affect occupational and public health by emitting pollutants during routine operation or accidental events. A large variety of materials may be used in manufacturing of photovoltaic devices; some may be released as by-products of normal or abnormal plant operations. Table I lists some feedstock materials used in PV manufacturing which are toxic, carcinogenic, pyrophoric or flammable. The actual hazard to health posed by these materials depends on their inherent toxicological properties, and the intensity, frequency, and duration of human exposures. In turn, potential occupational and public exposures depend on the availability and efficiency of safety and pollution control systems. Although manufacturing facilities may produce liquid, solid, and gaseous effluents, only gaseous effluents are likely to present acute hazards to public health. Liquid and solid wastes may also be dangerous, but the public can only be exposed through indirect pathways, i.e., in

Table I. Hazardous materials used in photovoltaic-cell manufacturing

Material	Source	PEL* (ppm)	STEL† (ppm)	IDLH‡ (ppm)	ERPG-2§ (ppm)	Comments
Arsine	GaAs CVD	0·05	—	6	—	Highly toxic
Cadmium compounds	CdTe and CdS deposition	0·01 mg/m^3 (dust) 0·002 mg/m^3 (fumes)	—	—	NA	Suspected carcinogenic
Carbon tetrachloride	Etchant	5	10		100	Toxic, potent greenhouse gas
Chloro-silanes	a-Si and x-Si deposition	5	—	800	—	Decomposes to toxic fumes
Diborane	a-Si deposition	0·1	—	40	1	Highly toxic
Hydrogen	a-Si deposition	—	—	—	—	Fire hazard
Hydrogen fluoride	Etchant	3	—	30	20	Noxious, corrosive
Hydrogen selenide	CIS sputtering	0·05		2		Highly toxic, flammable
Hydrogen sulfide	CIS sputtering	10	15	—	30	Highly toxic, flammable
Phosphine	a-Si deposition	0·3	1	—	—	Highly toxic, flammable
Silane	a-Si deposition	5	—	—	—	High fire and explosion hazard

*PEL: The permissible exposure limit is defined by OSHA as the time-weighted average threshold concentration above which workers must not be exposed during work-shifts (8 hr/day, 40 hr/week).

†STEL: the threshold limit value, short term exposure level is defined by the American Conference of Governmental Industrial Hygienists (ACGIH) as the maximum concentration to which workers can be exposed for a period up to 15 min, provided not more than four excursions per day are permitted with at least 60 min between exposure periods and provided that daily PEL is not also exceeded.

‡IDLH: the immediately dangerous to life or health concentration is defined by the National Institute for Occupational Safety and Health (NIOSH) as the maximum concentration from which one could escape within 30 min without any escape-impairing symptoms or any irreversible health effects.

§ERPG-2: the emergency response planning guideline-2, is defined by the American Industrial Hygiene Association (AIHA) as the concentration below which nearly all people could be exposed for up to one hour without irreversible or other serious health effects or symptoms that would impair their ability to take protective action.

drinking water, and such exposures can be more easily monitored and controlled. Hence, these wastes may present chronic, but not acute risks to public health.

Crystalline silicon solar cells

Commercial crystalline-Si solar cells are primarily of the single-crystal and polycrystalline type. The occupational health and environmental issues related to these technologies are examined herein.

Occupational health issues

The occupational health issues are related to chemical burns and inhalation of fumes from hydrofluoric acid (HF) and other solutions of acids (e.g., HNO_3) and alkalis (e.g., NaOH) used for cleaning wafers, removing dopant oxide, and cleaning the reactor. Dopant gases and vapors (e.g., $POCl_3$, B_2H_6), also are hazardous when inhaled. $POCl_3$ is liquid, but in a deposition chamber it can generate toxic P_2O_5 and Cl_2 gaseous effluents. Inhalation hazards are controlled with properly designed ventilation in the process stations. Other occupational hazards are related to the flammability of silane (SiH_4) and its byproducts from silicon nitride deposition and the fabrication of x-Si layers via plasma enhanced chemical deposition (PCVD); these hazards are discussed later.

Environmental issues

The environmental issues are the generation of liquid and solid waste during wafer slicing, cleaning, and etching; gas emissions and liquid and solid waste generated during solar cell processing, and the production of solid waste during module assembly. The slicing of wafers also results in solid waste (e.g., stainless-steel wire, and abrasive slurry composed of silicon carbide), and liquid waste (e.g., mineral-oil-based or glycol-based, water-soluble slurry).

Safer and environmentally friendlier alternatives

Oil-based slurry is commonly used by the PV industry; the waste produced is more damaging to the environment and requires more extensive wafer cleaning than waste left from glycol-based slurries. Replacing oil-based slurries with glycol-based ones, or, even better, with water-based slurries will eliminate the potential for environmental damage. The added costs and the process changes needed for the PV industry to switch over must be investigated.

The photovoltaic junction in Si layers is formed by diffusion in either belt-furnaces or tube-furnaces. The later traditionally use $POCl_3$-liquid source dopant, which generates toxic effluents and requires frequent cleaning of the diffusion tubes with HF solutions. Belt-furnaces are more environmentally friendly because they use water-soluble, non-toxic, spin-on or spray-on dopants or vapor dopants and do not require cleaning with HF.

Edge trimming to remove electrical shorts between the front and back junction can be done either by laser cutting or plasma etching. The most common technique is plasma etching using carbon tetrafluoride (CF_4) and oxygen. However, CF_4 is a very potent greenhouse gas and the industry is looking for safer alternatives and for better effluent treatments that include CF_4 capture and recycling. Safer alternatives and recycling options are actively investigated by the Integrated Circuit (IC) industry.

The anti-reflection coating on x-Si cells is commonly placed by silicon nitride deposition using SiH_4, a pyrophoric gas. A safer non-pyrophoric alternative was used successfully by the IC industry; this alternative can also be used in the PV industry.

Flux, which is applied to cell interconnection strips before soldering, leaves residues on the cell surfaces that typically are cleaned with chlorofluorocarbon (CFC) compounds; these CFCs are known to deplete atmospheric ozone. Recently, low-residue fluxes have become available that could be left on the solar cell after soldering; this can eliminate the CFC usage in PV manufacturing facilities.[8]

Waste minimization

Waste minimization can be effective in crystalline-Si cell manufacturing, as demonstrated by successful programs in the laboratory and in plants. For example, the Photovoltaic Device Fabrication Laboratory at Sandia National Laboratories reduced waste generation by 75% since 1990 by substitution, re-use, and recycling. Siemens Solar Corporation reduced by about 20% the caustic waste generated by the etching process that removes saw-damage after wafer slicing, by switching from ID saws to multiple-wire saws. Wire-sawn wafers require less etching to remove saw damage. At the same time, wire sawing gives 52 wafers per inch of material, which is a 65% increase in productivity. Being environmentally friendly can improve the bottom line!

Additional waste minimization options that need to be investigated include recycling of stainless-steel cutting wires, and recovery of the SiC in the slurry.[8] Either acid or alkali (e.g., NaOH) solutions are used for etching. Also, while many facilities dispose of the spent etching bath as hazardous waste, in-house neutralization apparently can be accomplished at a fraction of the cost of disposal.

Amorphous silicon solar cells

Amorphous-Si cells can be made by several different processes, including glow discharge, chemical vapor deposition, and reactive sputtering. In glow discharge systems, the a-Si layer is deposited from SiH_4, or mixtures of SiH_4/H_2, SiF_4/H_2, or $SiH_4/GeH_4/H_2$. Because of the low efficiency of the deposition processes (e.g., 10–20%), a relatively large volume of these gases is used.

Occupational safety issues

The main safety hazard of this technology is the use of SiH_4 gas, which is extremely pyrophoric. The lower limit for spontaneous ignition of SiH_4 in air ranges from 2% to 3%, depending on the carrier gas. If SiH_4 escapes in a partially confined space at flow rates above 300 lpm, an explosion is likely, but even smaller flow rates may cause an explosion if the gas accumulates. Releases in open air usually ignite and burn smoothly; under appropriate circumstances, burning or flaring can serve as a mechanism for preventing an explosion. In confined chambers where the air is not turbulent, SiH_4 has a stable flame, and these flames do not tend to 'blow off'. SiH_4 does not easily mix, but it has the tendency to form 'pockets' in another gas, especially in hydrogen; if mixing is incomplete, a pyrophoric concentration may exist locally even if the SiH_4 concentration in the carrier gas is less than 2%. Some basic options on SiH_4 safety are summarized in Table II; more details can be found elsewhere.[9] In addition to SiH_4, hydrogen used in a-Si manufacturing and in small quantities in crystalline-Si manufacturing, is also explosive. Most PV manufacturers use sophisticated gas-handling systems with safety features to minimize the risks of fire and explosion. Some facilities use bulk storage of silane and hydrogen in tube trailers to avoid frequent

Table II. Basic options for preventing hazards from silane

- Store the minimum volumes possible.
- Store silane cylinders separately from toxic, corrosive, flammable, oxidizing, and water-reactive materials.
- Locate the scrubber for SiH_4 outdoors, or in a very well ventilated area.
- Purge the storage cabinet continuously with a high-velocity air flow, probably through several ports, to assure air is mixed with SiH_4.
- Purge storage cabinets continuously with N_2.
- Get excess-flow limiters (typically a 6 mil orifice) in the cylinder valves.
- Get explosion resistant cabinets with pads, roof, double fences, and fire protection sprinklers.
- Install gas monitors with automatic shut-off valve at the cylinder.
- Dilute the SiH_4/H_2 effluent from the process or the scrubber with N_2 to lower the SiH_4 concentration below 0·5% before it mixes with air.
- Make all exhaust lines of non-combustible material.
- Adequately purge the oil reservoir chamber of vacuum pumps with N_2 to prevent accumulation of SiH_4.
- Separate the vent- and reactor-exhaust lines so that SiH_4 does not mix with air.

Table III. Toxic gases hazard prevention options

- Limit the inventory of toxic gases to several months (at most) supply.
- Whenever possible, use low concentration (2–10%) sources of toxic gases.
- Purchase cylinders equipped with the smallest flow-restrictor that process- and safety-requirements may allow (e.g., 0·006 in).
- Segregate highly toxic materials from other chemicals and combustible or flammable substances by storing them outdoors, or in a room or a gas cylinder cabinet with adequate ventilation and fire protection.
- Install excess-flow valve and a pneumatically driven valve with electric switching of a fail-safe design.
- Establish firm procedures for changing gas bottles and follow them vigilantly.
- Install gas-monitoring points in and outside each gas-cylinder cabinet.
- Use coaxial double piping with an outer jacket of inert gas, monitor jacket's pressure, and interlock with the automatic cylinder shut-off valve.
- Enclose any single lines in purged raceways.
- Purge air from gas-cabinet and connect raceways to a treatment system or a safe vent.

changes of gas cylinders. Bulk storage decreases the probability of an accident, since trailer changes are an infrequent, well-scheduled special event which can be treated in a precise well-controlled manner, under the attention of the plant's management, safety officials, gas supplier and the local fire-department officials. On the other hand, if an accident occurs, the consequences can be much greater than an accident involving gas cylinders.

Toxic doping-gases (e.g., AsH_3, PH_3) are used in quantities too small to pose any significant public health or environmental hazards. Leakage of these gases, however, can cause significant occupational risks and continuous vigilance by management is needed to safeguard personnel. Applicable prevention options are summarized in Table III, and discussed in earlier articles.[9,10]

Public health and environmental issues

For a-Si facilities that use bulk silane, the potential consequences from a catastrophic release need to be assessed on a facility-specific basis. No significant environmental issues have been identified with this technology.

Cadmium telluride solar cells

CdTe solar cells can be manufactured by several deposition techniques, such as close-spaced sublimation, electrodeposition, and spraying. The CdS films needed for heterojunction formation usually are formed by spray pyrolysis or solution growth. The efficiency of material utilization in these processes ranges from a high of 90% for electrodeposition, to a low of 5–10% for spray pyrolysis.

Occupational health and safety issues

The occupational health hazards presented by Cd and Te compounds in various processing steps vary with the compounds' toxicities, their physical state, and the mode of exposure. No clinical data are available on human health effects associated with exposure to CdTe. Research at the National Institute of Environmental Health Sciences (NIEHS), done at the request of BNL and Siemens Solar Corporation, compared the toxicity of CdTe, CIS, and CGS in animal experiments simulating ingestion and inhalation; CdTe was shown to have the highest toxicity and CGS the lowest.[11,12] One of the parent compounds, Cd, which is considered both toxic and a lung carcinogen, is regulated in the US by the Occupational Safety and Health Administration (OSHA). OSHA indicated that they consider all Cd compounds (including CdTe) to be toxic.

In production facilities, workers may be routinely or accidentally exposed to Cd compounds through the air they breathe, and by ingestion from hand-to-mouth contact. Inhalation is probably the most important pathway because of the larger potential for exposure, and higher absorption efficiency of Cd compounds through the lung than through the gastrointestinal tract. The physical state in which the Cd compound is used or released to the environment is another determinant of risk. Processes in which

Cd compounds are used or produced as fine particles or fumes, present larger health risks. Similarly, those involving volatile or soluble Cd compounds also must be more closely scrutinized. The facilities using Cd compounds should establish an ongoing industrial-hygiene program that includes biomonitoring and wipe-sampling. Because spray pyrolysis has very low utilization efficiency, it generates a large quantity of by-products and fine particles. Some of these materials will be deposited on the reactor's wall, requiring periodic scraping or chemical removal and cleaning. The large fraction remaining will be contained in the exhaust gas. In this type of process, hazards to workers may arise from preparing the feedstock, from fume and vapor leaks, and maintenance operations (e.g., scraping and cleaning). Because of the acute health-hazard from Cd and CdO fumes that could be released accidentally from a spray pyrolysis unit, special precautions are needed to protect workers (e.g., multi-cycle evacuation of the deposition chamber before opening it).

There are few publications on monitoring employee exposures in the manufacturing of photovoltaic cells; some data were collected through personal communication. In CdTe facilities, no detectable levels of Cd were reported from monitoring people during maintenance operations (CdTe physical vapor deposition system, and CdTe oven overhaul), during daily operations involving physical vapor deposition, nor in sandblasting Cd targets. However, area samples taken in line with the exhaust flow during maintenance of the physical vapor deposition system were 0·03 mg/m^3, which is above the TLV of 0·01 mg/m^3. Initial wipe samples taken in the deposition and sample preparatory laboratories ranged from below detection to 0·6 mg, but dropped below detectable limits after good housekeeping procedures were established. The implication here is that there is a potential for Cd dust to accumulate in facilities where the rooms are poorly ventilated or good housekeeping is lacking.

Public health and environmental issues

The health of the public may be affected from chronic exposure to Cd compounds released to the environment as a by-product of different manufacturing steps, or as a waste from the uncontrolled disposal of spent photovoltaic modules. The magnitude of potential releases from manufacturing depends on the methods and controls implemented in each facility. For example, a 10 MWp PV fabrication plant, using electrodeposition with an efficiency of 90% in forming a 2 μm CdTe layer, would generate only 11 kg/yr of Cd and 12 kg/yr of Te, mostly as ions in solution. Therefore, electrodeposition poses minimal public-health hazards during routine operations. Only if accidentally the electrodeposition batch becomes contaminated, or a spill occurs, may additional material need treatment.

A less efficient deposition process (e.g., spray pyrolysis with estimated efficiency of 10%), would generate about 950 kg of $CdCl_2$, CdO, HCl, H_2S and thiourea byproducts. Some of this material will be deposited on the reactor's walls, but most will be in a gaseous form in the exhaust stream. Under these assumptions, a 10 MWp plant may generate emission flow rates of about 0·45 kg/hr during an 8 hr day, for 250 days-per-year. According to the New York State Department of Environmental Conservation Guidelines, these emissions should be reduced by at least 60%, to 0·2 kg/hr, to meet the state's discharge limitations.

Hazard management and waste minimization

Occupational exposure to CdTe and its precursors may occur during module production, installation, maintenance, and waste disposal. Established precautions include continuous air- and wipe-monitoring, engineering controls, personal protective equipment, and prudent work practices (e.g., not eating, drinking, smoking in regulated areas, and good housekeeping). Good housekeeping plays a key role in controlling occupational health hazards. Accumulations of dust on overhead ledges, equipment, and floors in the workplace should be removed before some disruption, such as traffic or random air currents, re-entrains the dust and makes it airborne again.

Area and personnel monitoring should be used continuously to provide information on the type and extent of employees' exposure, assist in identifying potential sources of exposure, and gather data on the effectiveness of the controls. In addition, intensification and attenuation options need be considered. For example, using a deposition process with a higher efficiency would allow smaller inventories of chemicals, and changing from a powdered to a pelleted form of a chemical should reduce the probability of exposure. Similarly, automating a process can significantly reduce its potential hazard. Occupational exposures also can be reduced by either containing the operation, or isolating the workers from the operation by placing them in a clean room, a properly ventilated cab, or some distance from the source of exposure.

When other methods of control prove ineffective or non-feasible, ventilation is an important engineering control. Local ventilation is the most effective because it captures contaminants at, or near, their source and exhausts them outside the workplace. Local ventilation, and effective work practices should be used at all stages of CdTe handling, deposition, scribing, finishing, grinding, and also in recovery and equipment-cleaning procedures. Engineering controls also may be applied to mechanizing the oil changes by using quick-disconnect lines attached directly to waste-oil drums. These procedures will minimize the potential for airborne exposure.

Copper Indium Selenide Solar Cells

Copper Indium Selenide ($CuInSe_2$, CIS) thin-films can be formed by several processes, including co-evaporation (i.e., physical vapor deposition) of Cu, In, and Se, and selenization of Cu and In layers in H_2Se atmosphere. In the second method, Cu and In are deposited by electron-beam evaporation and sputtering techniques. Other options involve gallium sources and the formation of copper gallium selenide layers (CGS). Heterojunction typically is formed with CdS film. The health and safety issues related to CdS were discussed in the context of CdS/CdTe solar cells, above.

Occupational health and safety issues

There is limited information on the toxicity of CIS and CGS. As discussed earlier, limited animal testing comparing CdTe, CIS and CGS showed that CGS has the lowest toxicity, and that CIS is somewhat more toxic than CGS, but less so than CdTe.

The main safety issue in producing CIS cells is related to the highly toxic gas hydrogen selenide, which is used as feedstock in some processes. The accident-prevention options listed in Table III also apply here.

Measurements of airborne copper, indium, and cadmium from mechanical scribing and deposition operations on CIS/CdS molecules showed concentrations that were well below their threshold level values.

Hazard management

The options for substitution, isolation, work practices, and personnel monitoring discussed for CdTe are applicable to CIS manufacturing too. In addition, the use of hydrogen selenide in some CIS fabrication processes requires engineering and administrative controls to safeguard workers and the public from exposure to this highly toxic gas. Limited inventories, flow-restricting valves, and other safety options are required to safeguard occupational and public safety. Emissions of hydrogen selenide from process tools can be controlled with wet or dry scrubbing.[13] Scrubbers that can control accidental releases of this gas should be in place. Such systems are discussed elsewhere.[13]

FEASIBILITY OF RECYCLING SOLAR CELLS

Public support of PV energy is driven by the environmental benefits derived by replacing fossil fuel plants with PV systems. The recyclability of PV systems (at the end of their useful life) adds to the environmental benefits, and can further enhance market support. Also, recycling answers the public's concerns about some materials in PV modules (e.g., Cd, Pb), which can create barriers to market penetration.

Photovoltaic modules may contain small amounts of regulated materials, which vary from one technology to another (e.g., Cd, Pb, Se, Cu, Ni and Ag). Environmental regulations can increase the cost and complexity of dealing with end-of-life PV modules. If they were classified as 'hazardous' according to Federal or State criteria, then special requirements for material handling, disposal, record keeping, and reporting would escalate the cost of decommissioning. Therefore, there is an economic incentive to design modules that will not be hazardous, or to design them in such a way that they can be recycled at a reasonable cost. Lastly, some PV materials (e.g., In, Te) may reach availability constraints in multi-GW production levels.[14,15]

The photovoltaic industry and the DOE have followed a pro-active long-term environmental strategy to preserve the environmental friendliness of solar cells. Accordingly, options to recycle used solar cells and manufacturing waste are being investigated. Recent studies showed that PV recycling is technologically and economically feasible, but not without careful forethought.[15,16] A recycling program was outlined, based on current collection- and recycling-infrastructure, and on emerging recycling technologies. Metals from used solar panels in large centralized applications can be reclaimed in metal smelting facilities which use glass as a fluxing agent and recover most of the metals by incorporating them into their product streams. In dispersed operations, small quantities and high transportation costs make this option expensive.

For these operations as well as small-scale recycling, hydrometallurgical separations can be economical.[17,18] These processes start with physical separations of module frames, junction boxes and wires; then, the modules are fragmented, and metals are stripped in successive steps of chemical dissolution, mechanical separation, and precipitation or electrodeposition. Another option is to leave the glass substrate intact (and the SnO_2-conducting layer), potentially allowing their re-use for PV deposition. At the end, the mounts, glass, EVA, and a large fraction of metals are recovered (e.g., 80–96% of Te, Se, Pb). The remaining metals (e.g., Cd, Te, Sn, Ni, Al, Cu) are contained in a sludge which must be disposed of, or further recycled. For example, Cd-rich sludge from CdTe recycling is sent to INMETCO, where Cd is recovered, and eventually used as feedstock for NiCd batteries. The estimated total cost for this operation is approximately 4–5 ¢/W, excluding transportation.

The projected cost of collecting and transporting thin-film solar panels in large quantities from central locations is about 2 ¢/W, and from dispersed installations about 8–10 ¢/W. Therefore, the total cost of recycling in smelters thin-film PV modules or scrap from large installations is 4–5 ¢/W; from dispersed installations it is about 10–12 ¢/W. For comparison, the current total cost of disposal of large deliveries of trash in a local non-regulated landfill is about $100/ton (equivalent to 1 ¢/W). Disposing of hazardous waste costs about $0·50/lb for 55-gal drums; this is equivalent to 35 ¢/W for thin-film modules.

PV AND THE REDUCTION OF GREENHOUSE-GAS EMISSIONS

A discussion on environmental issues related to PV would be incomplete without highlighting the environmental benefits of the technology. In addition to being a renewable and clean technology (they do not emit any SO_2, NO_x, nor particulates), photovoltaics can also significantly contribute to alleviating the greenhouse effect. Several studies on this issue were presented in two recent workshops.[6,19]

In the following we highlight some examples from an on-going energy–environment–economic study conducted at BNL, using the model MARKAL to predict the penetration of central-PV and corresponding carbon emission reductions in the United States (US). MARKAL is a dynamic linear programming model, which describes all possible flows of energy, from resource extraction to energy transformation and end-use devices. The model predicts the evolution of a specific energy system over a specified period (e.g. 30–50 years), at the national, regional, or local level. Each energy technology or emission control technology is represented quantitatively by a set of performance- and cost-characteristics. Both the supply and demand sides are integrated and the model selects that combination of technologies that minimize the total cost of the energy systems. In optimizing the energy–economic system, the model explores a wide range of options. More than 200 technologies and options are described: energy conservation measures, higher efficiency devices, switching from coal or oil to natural gas, and switching from fossil fuels to renewable technologies. In addition to PV, the renewable technologies explored by the model are wind, solar-thermal, biomass fuels, waves, and ocean-thermal gradients. The model thus can evaluate the potential of PV in a competitive environment. The analysis examines two kinds of results. The first is the projected PV market penetration in the US. The second is the effect of such penetration on reducing US CO_2 emissions.

This study is based on certain projections of installed system cost for PV electricity generation application in the US, as well as cost projections on all competitive technologies. The PV price projections we introduced in the model are derived from 'learning curves' for specific 'progress ratios'.[20] A 'learning curve' describes how the cost of a product or system declines as a function of the cumulative capacity of a technology. The Progress Ratio (PR) expresses the rate at which the cost declines each time the cumulative production doubles. For example, a PR of 0·81 means that the cost of installed capacity decreases by 19% (i.e., the new cost is 81% of the previous cost) for each doubling of cumulative installed capacity. Cody and Tiedge[21] reviewed historical data for PV and reported PRs in the range of 0·7–0·81. Our preliminary simulations show that a PR of 0·81 for PV may not be sufficient to 'win' the competition (primarily advanced gas turbines and wind systems which are also improving), and that a PR of 0·78 or lower is needed to bring PV to the multi-GW range in the US. However, if the 'million-solar roof initiative' announced by the President of the US materializes, it may produce a 'forced' capacity that can drive PV penetration in the US to multi-GW levels even under a PR of 0·81. The total installed US capacity under this initiative is predicted to be 80 MW by the year 2000, 820 MW by 2005 and 3 GW by 2010.[22] Introducing in MARKAL these capacities for 2000 and 2005, we predicted that 2 GW of total capacity is needed by 2010 to create a sufficient momentum for price reductions to continue by themselves. We predicted that the PV installations in the South-West (SW) region of the US (where the average solar insolation is 2200 kWh/m^2/yr) would reach 20 GW by 2025 (Figure 1). An additional 20 GW would be installed in the NE part of the US where the solar insolation is only 1600 kWh/m^2/yr but the electricity prices are higher than the US average (Figure 2). It is noted that the US-DOE projections are significantly lower than our predictions.

We also investigated PV market penetration under a scenario of carbon emissions' stabilization. We predicted total capacity penetrations in the US market when carbon emissions from 2010 through 2030 are constrained to be 20% below the 1990 levels. These carbon constraints have the same effect as the forced capacity scenario, but the 20-GW capacities will occur earlier than 2025 (Figures 1 and 2). Under

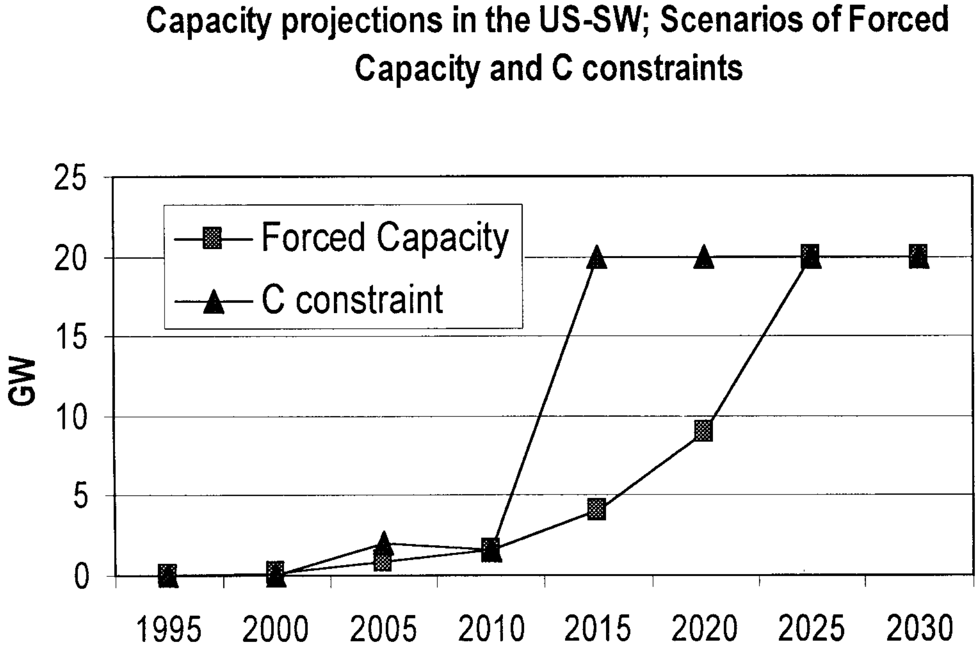

Figure 1. Capacity projections in the US-SW; scenarios of forced capacity and C constraints

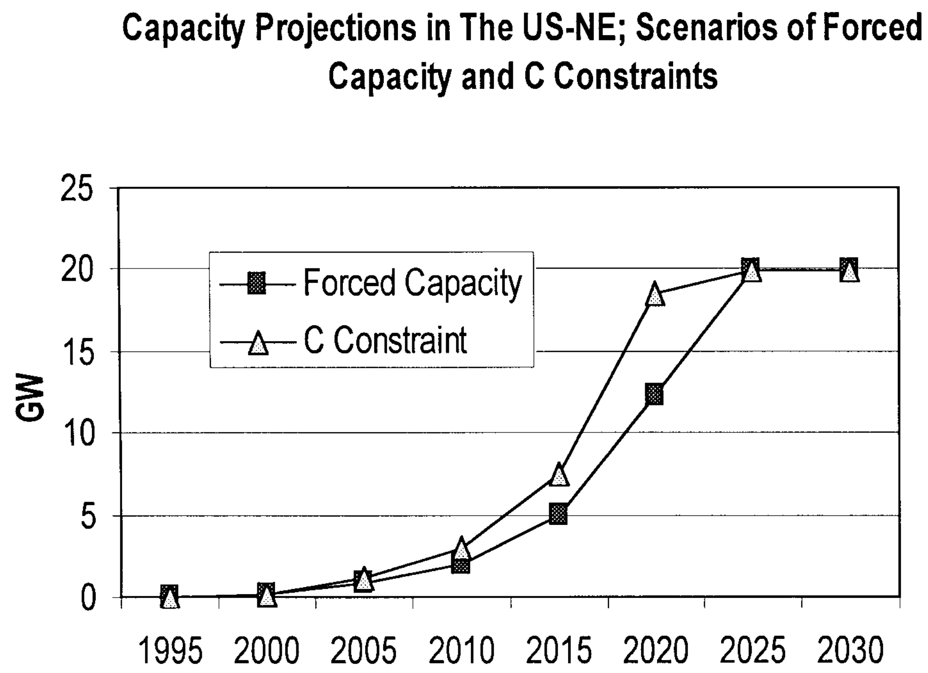

Figure 2. Capacity projections in the US-NE; scenarios of forced capacity and C constraints

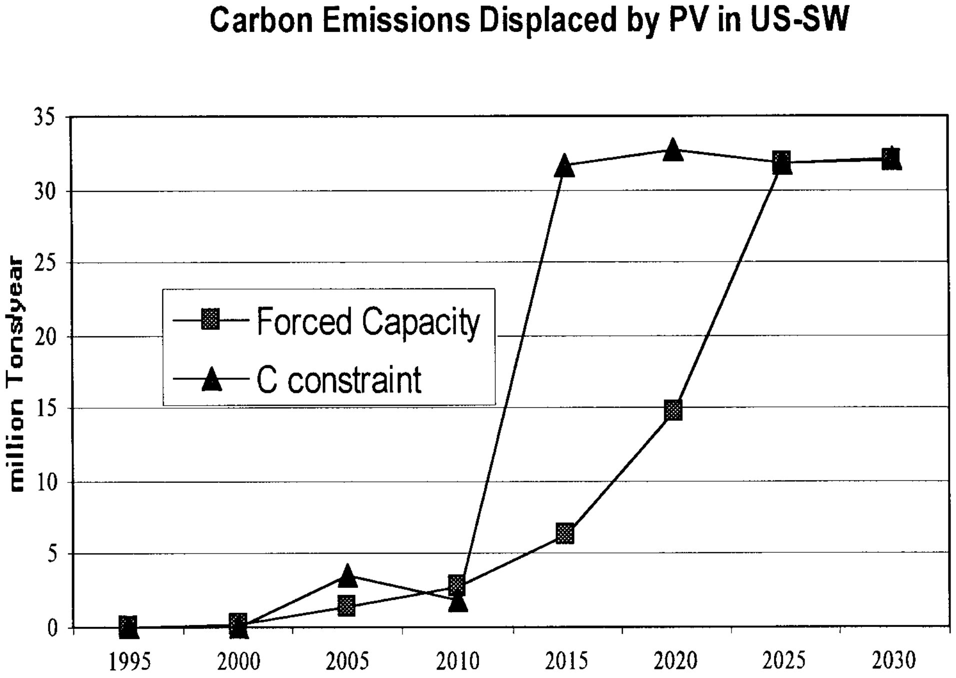

Figure 3. Carbon emissions displaced by PV in US-SW

these scenarios, PV will enable carbon emission reductions of about 33 million tons per year by the year 2025 in the SW region of the US (Figure 3) and an additional 28 million tons per year in the NE region (Figure 4). These carbon emission reductions could be the beginning of a longer-term trend as the market share of PV technologies is expected to keep increasing after 2030.

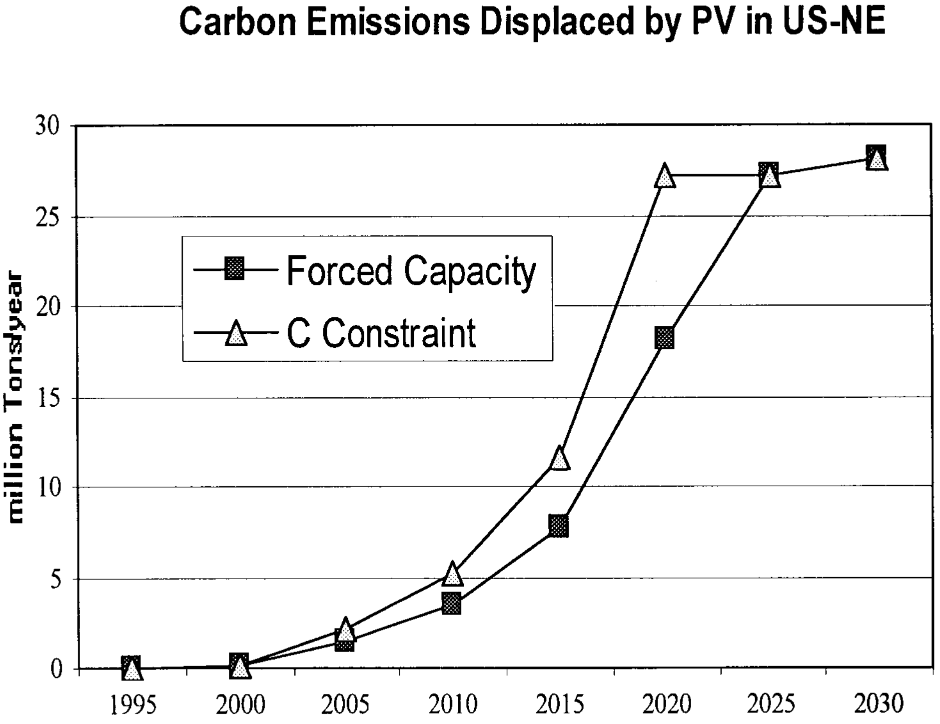

Figure 4. Carbon emissions displaced by PV in US-NE

CONCLUSION

The manufacture of photovoltaic modules uses some toxic and explosive gases, corrosive liquids, and suspected carcinogens in solid form. Routine conditions in manufacturing facilities should not pose any threats to health and the environment. Quality control in these facilities demands especially clean conditions, and air concentrations of contaminants in occupational space should be much lower than threshold exposure limits. However, as a general guidance, all facilities working with hazardous materials should continue to control exposures by monitoring, engineering controls, personnel protective equipment and good work practices. Ongoing efforts are needed in waste minimization and recycling.

Hazardous materials could adversely affect occupational and, in some instances, public health during accidental conditions. Such hazards arise primarily from the toxicity and explosiveness of specific gases. Accidental releases of hazardous gases and vapors can be prevented through the choice of safer technologies, processes and materials, better material utilization, employee training and safety procedures. As the PV industry approaches these issues and mitigation strategies in a vigilant, systematic way, the risk to the industry, the workers and the public would be minimal. This is especially important in view of anticipated multi-hundred MW production facilities to meet the increased demand for PV and help stabilize carbon emissions.

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