United States Environmental Protection Agency
Research and Development

Industrial Environmental Research Laboratory
Cincinnati OH 45268

EPA-600/S7-82-066 Mar. 1983

EPA

Project Summary

Photovoltaic Energy Systems: Environmental Concerns and Control Technology Needs

Paul D. Moskowitz, Paige Perry, and Israel Wilenitz

Technical and commercial readiness for alternate photovoltaic energy systems, and waste streams from three different photovoltaic systems are examined. At present, specific emission standards for this industry do not exist and measurements of wastes produced by existing manufacturers are not available. Thus, emission estimates presented are based upon design engineering studies of hypothetical facilities. Because of the widespread use of many of the materials used in this industry, available control experience and technologies used in other industries may ultimately be applied to photovoltaic plants. This analysis suggests that some uncontrolled waste streams could be declared toxic or hazardous under various provisions of the Clean Air, Clean Water, and Resource Conservation and Recovery Acts. Although some processes could emit large quantities of pollutants, these can be controlled using available technology. Other processes may emit small quantities of more toxic pollutants which will probably not be directly controlled unless significant health hazards are identified. Environmental problems in installation and operation are probably associated with large central-station applications; no significant effects are expected from small decentralized applications. Decommissioning of broken or degraded photovoltaic systems will generate large quantities of solid waste which can be simply disposed of in a landfill or perhaps recycled. Disposal of spent photovoltaic devices containing cadmium may present unique hazards.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Identification and analysis of environmental concerns and ways to mitigate them for any energy industry before it becomes fully commercialized can limit potential investment costs while simultaneously minimizing environmental and public health risks. This report updates previous studies by the U.S. Environmental Protection Agency (EPA) which examine potential health and environmental risks and control methodology related to photovoltaic energy systems. This analysis should provide background information about potential health and environmental effects to planners concerned with research and regulatory priorities, and federal, state, and county officials engaged in pollution control permitting programs.

In this spirit, this study reviewed the technological readiness and examined environmental concerns related to commercialization of photovoltaic energy systems. The final report describes the technical and commercial readiness of photovoltaic energy systems; reviews refining, fabrication, installation, operation and maintenance, and decommissioning alternatives associated with the industry; identifies methods which are likely to be used to reduce pollutant release; describes environmental regulations that are or might be applied to an installed industry; and examines the hazard potential of wastes generated during the refining of specific materials and the fabrication of different photovoltaic cell types. The information presented is based upon an extensive analysis of the literature, supplemented by discussions with different individuals in the governmental and private sectors.

Of the several phases in the life cycle of photovoltaic systems, the refining of materials and subsequent cell manufacture were most intensively examined because they represent the major steps from which pollutants are released. Waste streams and pollution control methods for the following three different photovoltaic systems were considered: (1.) silicon n/p cells produced by ingot growing; (2.) silicon metal/insulator/ semiconductor cells produced by ribbon growing; (3.) cadmium sulfide/copper sulfide backwall cells produced by spray deposition. These three systems cover a range of manufacturing options and materials likely to be used in near-term commercialization activities.

Measurements of waste streams from existing manufacturers of photovoltaic devices are not publicly available, and therefore design engineering studies of expected typical facilities were prepared. From these, sources and types of pollutants were estimated for each of the production processes, as well as from the installation, operation and maintenance, and decommissioning of photovoltaic systems. Estimates were based on a 10 MWp/year plant and for a national annual production rate of one gigawatt peak. Plant emission rates are presented on a kg/day basis and provide background information for personnel engaged in pollution control permitting programs. Estimates presented on a per GWp basis reflect national production rates in 1990 and should be more useful for administrators in determining research and regulatory priorities.

Conclusions

Large growth in the photovoltaics industry is expected in the next two decades. In the year 2000, it is estimated that total installed capacity will range from (0.2 to 2.0) x 10^5 MW_e. A variety of materials and cell concepts are now being examined for use in different markets: small-remote (10 kWp) for non-grid-connected applications, and small (10 kWp) to large (100 MWp) systems for use in residences, commercial and industrial settings, and central-station electricity generation.

Single-crystal silicon cells are currently produced commercially and serve as the standard of comparison for new materials and concepts being developed. Production of these cell types is costly; several alternatives are being investigated. Processes near commercial application include both ingot casting and ribbon growing for use in semicrystalline silicon solar cells. Inexpensively produced thin films from such specialized materials as cadmium sulfide/copper sulfide, polycrystalline gallium arsenide, and amorphous silicon have the potential to yield photovoltaic cells at comparatively low production costs.

Presently, specific emission standards for this industry do not exist, and regulations on existing facilities range from none to specification of methods of hazardous waste disposal. Standards developed for related industries, processes, or for specific pollutants, may affect control technology requirements in this industry. Potential requirements under review by the EPA include National Emission Standards for Hazardous Air Pollutants (NESHAPs) for arsenic and possibly cadmium, and New Source Performance Standards (NSPS) for particulates from electric arc furnaces and volatile organic compounds from degreasing operations; Clean Water Act effluent limits applicable to the electronics industry; and, Resource Conservation and Recovery Act standards for control of a variety of specific toxic and hazardous wastes, including a number from electroplating and degreasing operations.

Estimates of uncontrolled emission rates from production of silicon ingot photovoltaic cells are presented in Table 1. Similar tables of pollutant emission rates are presented in the full report for cadmium sulfide and silicon ribbon cell production processes.

Results of the completed analyses suggest that several processes could emit potentially large quantities of pollutants. Large quantities of fine particulates are discharged from electric arc furnaces in producing metallurgical-grade silicon (MG-Si) for a number of uses (e.g., in semiconductors). However, silicon demand by the photovoltaic industry represents only a small fraction of total producton and therefore is not expected to result in a significant increase in these emissions. Further refinement of MG-Si by existing techniques consumes large quantities of hydrochloric acid, which must ultimately be disposed of. Etching of single-crystal silicon ingots generates large quantities of spent acids, including hydrofluoric, which may require controlled disposal. Plasma etching may eliminate the need to use wet etching processes. Silicon ribbon production, as hypothesized, is a much cleaner production process than ingot growing. Nevertheless, small quantities of solvents and silver-based inks may require careful control. Cadmium sulfide photovoltaic cell production is characterized by the use and release of cadmium and the production of large quantities of spent plating solutions containing various metals. These may require controlled disposal.

Table 2 summarizes control alternatives that may be used in this emerging industry. Because of the widespread use of many of the materials in other industries, available control experience and technologies may ultimately be applied to the photovoltaics industry. The final degree of control is likely to be more precisely defined by specific design engineering studies seeking compliance with specific standards.

Other processes may emit small quantities of more exotic pollutants (e.g., boron trichloride, phosphorous oxychloride, phosphine) which will probably not be directly controlled unless significant health hazards are identified. To the degree that processes are integrated within plants and automated, controls implemented to reduce major pollutant waste streams may also reduce discharges of these more exotic pollutants.

The most significant environmental problems in operation of photovoltaic devices are expected to be associated with large central-station applications. Herbicides may be used to control plant growth near photovoltaic arrays. Also, it has been speculated that these facilities may produce micro- or meso-scale changes in the physical environment. Subsequent effects on species diversity, standing biomass, wind, temperature, and humidity have been hypothesized.

Decommissioning of broken or degraded photovoltaic systems will generate large quantities of solid waste. Most of these wastes will be nonhazardous and can be disposed of in a landfill or recycled. Disposal of spent photovoltaic devices containing cadmium may present unique problems. Centralized collection by a utility owning a central-station array or maintaining a large number of decentralized systems will probably require disposal in controlled landfills. Decentralized disposal by individual homeowners, however, could result in the release of

Table 1. *Pollutant Emission Rates from the Production of Silicon Ingot Photovoltaic Cells*

Activity	Process Step	Pollutant	Medium	(kg/Day*) /Plant	(MT/YR) /GWp
Silicon Production	Carbothermic Reduction of Silica	SiO as SiO_2	Vapor	1,377	48,180
		Ash	Vapor	33	1,140
		CO	Vapor	5,895	206,340
	Silicon Purification by Siemans Process	Silicon dust loss from size reduction	Vapor	0.51 - 1.06	18 - 37
		Distillation bottoms ($SiCl_4$)	Liquid	1,160 - 2,000	40,600 - 70,000
		Noncondensibles (hydrogen)	Vapor	283	9,900
		Vapor Deposition by-product (63% $SiCl_4$)	Liquid	8,753	306,370
	Silicon Purification by Union Carbide Process	Silicon dust loss from size reduction	Vapor	3.5	124
		Waste settler discharge (79% $SiCl_4$)	Liquid	369	12,921
		Filter waste stream (43% H_2, balance chlorosilanes)	Vapor	38.6	1,351
		Stripper overhead (73% chlorosilanes)	Vapor	27.6	965
		Product melter loss (Silane and hydrogen. Argon not included)	Vapor	2.3	81
Cell Manufacture	Ingot Forming and Doping	Dust loss from crushing	Vapor	1.7	60
		BCl_3	Vapor	0.0009	0.031
		Crucible scrap (Si)	Solid	25.7	900
	Wafer Cutting and Etching	Silicon chips and dust	Solid	197	6,890
		Slurry (oil, clay, and SiC)	Liquid	30.6	1,070
		Etching liquor (12% SiF_4 88% mixed acids)	Liquid	1,647	57,640
		Etching vapors (hydrogen rate given, but also some fraction of liquor vaporized)	Vapor	7.7	270
	Junction Formation	$POCl_3$ dopant	Vapor	0.0009	0.03
	Wafer Edge Grinding and Etching	Silicon dust (under water spray)	Liquid	1.7	61
		Etching liquor (mixed acids)	Liquid	(?)	(?)
		Etching vapors (SiF_4 and H_2)	Vapor	42.3	1,480
	Electroless Plating and Soldering	Spent Ni plating solution	Liquid	85	2,990
		Acetone	Liquid	61	2,140
		Photoresist (urethane varnish and titanium dioxide)	Liquid	21 L	[740 m^3]
		Rinse water	Liquid	28	1,000
	Application of Antireflective Coating	Exhaust (60% HCl, 33% SiH_2Cl_2)	Vapor	0.15	5.2
		Si_3N_4 deposit on reactor walls	Solid	0.013	0.45
	Testing, Interconnecting and Encapsulating		NEGLIGIBLE		

*Plant Capacity 10 MWp/yr., and 350 working days/yr.

Table 2. *Review of Control Technology Alternatives*

Media/Category	Pollutants	Control Technology	Comments
1. Atmospheric			
1.1 Gas - Combustible	*CO, H, Chlorosilanes*	*CO combustion, air dilution, chlorosilanes combustion to form muriatic acid*	*Technology commonly employed; limits must be identified.*
1.2 Gas - Other	BCl_3, $POCl_3$, PH_3, *acids, solvents, (HCN)*, F*	*Air dilution, treat in lime scrubber and discharge liquor to lagoon*	*Design studies required to achieve limits.*
1.3 Dust	*Metals, Si, Cd,*	*Bag filters or cyclones*	*97 to 99% removal.*
2. Liquid			
2.1 Acid	*HF, HCl, Acetic,* HNO_3, H_2SO_4	*Neutralization*	*Impervious lagoon, overflow liquid may be hazardous; sludge will be hazardous.*
2.2 Metals	*Cd, Cu, As, Ni, Si*	*Flocculation (lime, alum, ferric salts, polyelectrolytes)*	*Flocculation technique must be identified. Effective standards must be met and sludge will require control.*
2.3 Other	*Chlorosilanes, solvents, slurry, cutting oils*	*Process revisions, distillation*	*Chlorosilanes could be feedstock.*
3. Solid			
3.1 Hazardous	*Cd, F and other compounds*	*Three alternatives - resale, recycle, disposal in controlled landfill*	*Metals and F noted under RCRA guidelines.*
3.2 Nonhazardous	*Si compounds*	*Resale or disposal in municipal landfill*	

**HCN may be a by-product of CdS cell production.*

small quantities of cadmium to the atmosphere (from combustion at municipal incinerators) or to terrestrial and aquatic systems (from disposal in municipal landfills).

Recommendations

On the basis of this analysis, the following topics may require further investigation:

(i) Measurement of Existing Waste Streams - Analyses of risks from photovoltaic energy systems are based upon design engineering estimates of wastes emitted from expected typical facilities. Sampling and chemical analyses from existing facilities are required to support the findings of these engineering studies or to identify inadequacies.

(ii) Regulation of Existing Industry - At the present time, efforts to control wastes from the existing industry vary. Some state and county officials engaged in the regulation of the existing industry need information relating to problems likely to be encountered, and methods which could be employed to control these problems. A large number of regulations exist, or are being developed, for related industries, processes, and pollutants. The potential applicability of these regulations to this industry needs to be examined in greater detail.

(iii) Technology Transfer - Manufacture of photovoltaic devices may require use and disposal of large numbers of chemicals; some may be toxic or hazardous. Control experience obtained for these materials in related industries should be made available to manufacturers of photovoltaic systems before facilities are actually constructed. Design engineering studies and field application of control techniques may ultimately be required to demonstrate their cost-effective applicability to this industry.

(iv) Evaluation of New Processes - Alternative materials and fabrication processes are being rapidly developed. Environmental data, however, are not being assembled at the same rate. Thus, existing knowledge about processing techniques, materials, and potential control methods is limited. Ongoing efforts are required to eliminate this void. Identification of control needs, prior to full-scale commercialization of these new technologies, can reduce total design engineering cost while minimizing potential health and environmental risks.

(v) Micro- and Meso-scale Biological and Climatic Effects - A number of analysts have suggested that operation of large central-station photovoltaic plants in the Southwest may create micro- and meso-scale effects on biological communities and climate. Research and analysis are required to evaluate the magnitude of these risks.

☆U. S. GOVERNMENT PRINTING OFFICE: 1983/659-095/590

Paul D. Moskowitz, Paige Perry, and Israel Wilenitz are with Brookhaven National Laboratory, Upton, NY 11973.
***Benjamin L. Blaney** is the EPA Project Officer (see below).*
The complete report, entitled "Photovoltaic Energy Systems: Environmental Concerns and Control Technology Needs," (Order No. PB 83-137 380; Cost: $10.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
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