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PHOTOVOLTAIC ENERGY TECHNOLOGIES: EXAMINING PUBLIC AND OCCUPATIONAL HEALTH RISKS

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Summary

Health risks of photovoltaic energy systems arise from mining, processing and refining of raw materials and from fabrication, installation, operation and disposal of devices used to convert sunlight into electrical energy. Using an accounting approach, public and occupational health risks of four different photovoltaic cell alternatives are estimated quantitatively by examining systematically all steps in representative energy cycles. Detailed estimates of occupational mortality and morbidity from physical and chemical hazards are given. Health risks in fabrication facilities are given special attention. Results suggest that most occupational mortality and morbidity are probably due to risks normally encountered in day-to-day operation of any industrial operation. Exposures to chemicals could create health costs but these will probably be controlled. Estimates of impacts on the general public from byproducts emitted in the photovoltaic energy cycle are explored. Public health hazards from exposure to arsenic or cadmium emitted in the photovoltaic energy cycle appear to impose only minimal risk. Health hazards related to silicon exposure cannot be assessed quantitatively because of lack of toxicologic information.

1. Introduction

The main alternative energy sources to oil and natural gas for electricity generation in the U.S.A. are coal, nuclear and solar. Interest is now focused on solar alternatives, in part because of widespread public concern about the health and environmental risks of the competing energy technologies. The health and environmental risks of solar technologies, including photovoltaic energy systems, are usually considered small but it is now recognized that no energy technology is risk free.

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In this paper we examine energy system health costs of photovoltaic technologies. Potential occupational and public health risks are identified by systematic examination of all steps including the mining, processing and refining of raw materials and the fabrication, installation, operation and disposal for four photovoltaic energy systems: (i) silicon n–p single-crystal cells produced by ingot growing; (ii) silicon MIS cells produced by ribbon growing; (iii) CdS back-wall cells produced by spray deposition; (iv) GaAs cells produced by modified ingot growing. These alternatives cover a range of manufacturing options (*e.g.* ingot *versus* spray deposition) and materials (*e.g.* silicon *versus* arsenic) which might be used in future commercialization efforts. The generic design for the reference technologies was based on an existing 25 kW_p decentralized photovoltaic system. This system serves as a preliminary example of a photovoltaic plant, but with the three following important reservations on its applicability to the design of future installations.

(i) Structural material requirements greatly overestimate materials likely to be included in future designs.

(ii) Fabrication technology is rapidly advancing towards thinner and more efficient solar cells.

(iii) The system is based on an intermediate-load-sized facility and does not characterize large centralized facilities adequately, nor is it relevant to roof-top decentralized applications.

Because the system was conservatively designed, materials used exceed those likely to be required in future designs. As a result of these excessive material demands, health risks calculated probably represent upper limit estimates.

Photovoltaic technologies are undergoing rapid change, so it is unlikely that these specific technologies will emerge in large-scale production as described here. Examination of technologies for which considerable data are available, however, provides useful base information and a test case for developing risk analysis methods. This analysis should therefore help decision makers to formulate sound and workable public policies by (i) identifying methods and data to assess risks of photovoltaic energy systems, (ii) revealing health and environmental costs of producing electrical energy by photovoltaic energy systems, (iii) determining the steps within each energy cycle which impose the greatest risks and which need abatement measures, (iv) identifying risks associated with photovoltaic energy technologies to meet a given energy demand projection over a given time and (v) examining the scientific basis underlying controversial issues surrounding commercialization of the technologies.

2. Analysis method

Health effects analysis requires a comprehensive analytical framework for preparation of risk estimates through detailed examination of each step in the energy cycle. Brookhaven National Laboratory's Reference Energy System exemplifies the type of conceptual framework needed for health impact analysis [1]. This framework, which permits comparison of different energy systems, is widely used in analyzing the health effects of conventional technologies which have fuel supply impacts. It must be modified to assess adequately technologies such as photovoltaics in which many health costs are not associated with the fuel cycle but rather with the mining, processing and refining of raw materials and the fabrication, installation, operation and disposal of the devices used to convert sunlight into useful energy. Conventional technologies, of course, also have effects associated with such activities, but in risk analyses these have generally been ignored in favor of the large primary fuel cycle impacts.

Examinations of some material cycle effects have been completed [2 - 5], but uniform frameworks to prepare consistent and accurate analyses were not used and effects of photovoltaic technology fabrication were not analyzed in great detail. Thus the first step in this analysis was to define a simplified Reference Material System [6, 7] which displays all activities from material extraction to disposal. Key elements of the system include (i) end-use material demands, (ii) efficiency coefficients for all processes, *i.e.* the ratio of material output to material input, (iii) standardized labor productivity estimates for all processes, *e.g.* the amount of labor required to mine 1 ton of copper ore, (iv) occupational health and safety coefficients by process, *i.e.* worker days lost per 100 man years, and (v) environmental emission coefficients by process. Specification of a network structure and quantities (i) - (v) suffice to generate some of the occupational health and safety risks and environmental residuals produced by this technology. Other risks, such as occupational and public exposure to toxic chemicals, must be evaluated in the light of other factors including environmental dispersion, exposure and dose–response. There are also recognized problems in defining consistent boundaries of the material supply system. Efforts are under way to explore this problem using economic input–output analysis which incorporates effects throughout the economy [7].

3. Reference systems

The generic design for the reference systems, described in Table 1, was based on a 25 kW_p photovoltaic system built by the Lincoln Laboratory, Massachusetts Institute of Technology, and described by Watts *et al.* [8]. The system produces power to pump irrigation water at the University of Nebraska Field Laboratory. The solar array consists of 28 flat panels. The array output is fed into a building which houses system control equipment and inverters to convert the d.c. produced by the solar cells into a.c. at 220 V.

We scaled up linearly the labor and material requirements of the system to a sufficient number to produce 10^{12} Btu of energy over their operating

TABLE 1

Photovoltaic system characteristics[a]

Technical characteristics	*Value of characteristic for following systems*			
	Si n–p	*Si MIS*	*CdS*	*GaAs*
Nameplate design (kW_p)	5.6×10^3	5.6×10^3	5.6×10^3	5.6×10^3
Efficiency	0.14	0.10	0.10	0.14
Packing factor	0.80	0.80	0.80	0.80
Cell area (m^2)	4.0×10^4	5.6×10^4	5.6×10^4	7.7×10^1
Land area (m^2)	8.0×10^4	1.1×10^5	1.1×10^5	3.9×10^4
Concentration factor	1 ×	1 ×	1 ×	500 ×
Annual insolation (kW h m^{-2} $year^{-1}$)	1.8×10^3	1.8×10^3	1.8×10^3	1.8×10^3
Annual electricity production (kW h)	9.8×10^6	9.8×10^6	9.8×10^6	9.8×10^6
Lifetime electricity production (kW h)	2.9×10^8	2.9×10^8	2.9×10^8	2.9×10^8
Lifetime electricity production (Btu)	1.0×10^{12}	1.0×10^{12}	1.0×10^{12}	1.0×10^{12}

[a]Modified from ref. 8; a 30 year lifetime, a 100% load factor and a peak insolation of 1 kW m^{-2} are assumed.

lifetime (30 years), a standard measure for comparison with other energy technologies. Risks from storage and back-up supply systems are not considered here but are examined in other efforts supported by the Health and Environmental Risk Analysis Program, U.S. Department of Energy [9]. If these risks were included, total costs of photovoltaic energy systems would increase.

The information needed to compute materials required for fabrication of a given photovoltaic device includes not only a reference design for the construction of the device but also enumeration and description of the ancillary equipment required by the photovoltaic system to produce useful energy. Material and labor required to produce each component must be taken into account to evaluate the total impacts of the system.

Details of the assumptions used and estimates of the primary and secondary materials contained in each of the components for the four technologies examined are described elsewhere [8] and are summarized in Table 2. Since material demands are overestimated, estimated risks should be recognized as upper limits.

4. Emission estimates

Electricity production by photovoltaic energy systems, in contrast with that by fossil fuel alternatives, does not result in direct emissions. The pollutants generated in materials production and fabrication must be taken into account to identify public health risks.

In Fig. 1 the estimates of material flows from extraction to ultimate disposal for silicon, cadmium, arsenic and gallium (the primary materials used in the active portion of the solar cell) are shown. Emission estimates of

TABLE 2

Photovoltaic bulk material requirements (tons per 10^{12} Btu output)

Material	*Material requirement for each system*			
	Si n–p	*Si MIS*	*CdS*	*GaAs*
Primary				
As				0.06
Cd			0.36	
Ga				0.05
Si	20	7		
Secondary				
Acrylic (plastic)	3	5	5	168
Al	1604	2316	2503	907
Cement	2666	3721	3721	480
Cu	120	160	161	199
Glass	0.2	0.2	599	0.2
Fe and steel	1260	1416	1054	2155

Modified from ref. 8.

these materials to air were based on data in several reports [10 - 13]. The quantities of the materials in solid wastes were calculated by preparing a mass balance for each process:

solid waste = material input — (material output + air pollutant)

The quantities of water pollutants were not considered but may represent an important health and disposal concern. Emissions of other materials, *e.g.* sulfur oxides and nitrogen oxides, were not included in this analysis. Process efficiencies for some fabrication steps were taken from Bickler [14]. At disposal, we assumed that either 0% or 100% of the primary material in the active portion of the photocell was emitted into the atmosphere (*e.g.* landfill or complete incineration). An assumption of 100% atmospheric release is unrealistic but represents an upper bound estimate. The reference system also assumes no recycle of spent or waste materials. In practice, some recycle is likely; thus again the data represent upper limit estimates. The inclusion of recycling would also reduce some supply sector (*e.g.* mining) emissions.

As shown, the largest atmospheric emissions are in decommissioning. Decommissioning risks, however, may be an artifact of the analysis since all spent cells will not be incinerated at a single location nor will 100% of the material be exhausted to the environment. Excluding decommissioning, emissions generally increase in the following order: fabrication, preparation, extraction and refining. Fabrication facilities (the only new part of the cycle specifically introduced by photovoltaics) play a relatively minor role. From the material cycle, most of the residuals produced appear to be discharged as solid waste. Recycling would not only reduce materials needs with reduced

Cell Type, Process, Material		Resource Extraction		Preparation		Refining		Fabrication		Decommission	Totals
Silicon n-p, Ingot, Solar Grade Silicon[a]	A	$1.4x10^{0}$		$1.2x10^{0}$		$0.11-1.1x10^{0}$		$0.97-9.7x10^{-1}$		$0-2.0x10^{1}$	Air Pollutants $0.28-2.5x10^{1}$
	B	Resource Extraction	113.8	Preparation	108.1	Refining	97.4	Fabrication	20.4	Decommission	
	C			$4.5x10^{0}$		$1.1-0.96x10^{1}$		$7.7-7.6x10^{1}$		$2.0-0x10^{1}$	Solid Waste $11-9.0x10^{1}$
Silicon MIS, Ribbon, Solar Grade Silicon[a]	A	$1.9x10^{-1}$		$1.7x10^{-1}$		$0.15-1.5x10^{-1}$		$0.14-1.4x10^{-1}$		$0-7.1x10^{0}$	Air Pollutants $0.39-7.8x10^{0}$
	B	Resource Extraction	15.7	Preparation	14.9	Refining	13.4	Fabrication	7.11	Decommission	
	C			$6.3x10^{-1}$		$1.5-1.4x10^{0}$		$6.3-6.2x10^{0}$		$7.1-0x10^{0}$	Solid Waste $16-8.2x10^{0}$
Cadmium Sulfide, Spray Deposition, Cadmium[a]	A	$4.5-9.0x10^{-3}$		$4.3x10^{-2}$		$0.66-5.5x10^{-1}$		$0.72-7.2x10^{-3}$		$0-3.6x10^{-1}$	Air Pollutants $1.14-0.97x10^{-1}$
	B	Resource Extraction	1.80	Preparation	1.71	Refining	0.72	Fabrication	0.36	Decommission	
	C			$4.7x10^{-2}$		$9.2-4.4x10^{-1}$		$3.6-3.5x10^{-1}$		$3.6-0x10^{-1}$	Solid Waste $17-8.4x10^{-1}$
Gallium Arsenide, Ingot, Arsenic[a]	A	$1.3x10^{-2}$		$1.3x10^{-2}$		$0.20-1.38x10^{-1}$		$0.18-1.8x10^{-3}$		$0-6.0x10^{-2}$	Air Pollutants $0.46-2.26x10^{-1}$
	B	Resource Extraction	0.48	Preparation	0.46	Refining	0.18	Fabrication	0.06	Decommission	
	C			$7.0x10^{-3}$		$2.6-1.4x10^{-1}$		$1.2-1.2x10^{-1}$		$6.0-0x10^{-2}$	Solid Waste $4.5-2.7x10^{-1}$
Gallium Arsenide, Ingot, Gallium[a]	A	$1.9x10^{-3}$		$9.5x10^{-3}$		$0.36-3.6x10^{-3}$		$0.15-1.5x10^{-3}$		$0-5.0x10^{-2}$	Air Pollutants $1.2-6.6x10^{-2}$
	B	Resource Extraction	0.38	Preparation	0.36	Refining	0.15	Fabrication	0.05	Decommission	
	C			$1.05x10^{-2}$		$2.1-2.1x10^{-1}$		$9.9-9.9x10^{2}$		$5.0-0x10^{-2}$	Solid Waste $3.7-3.2x10^{-1}$

A, Air Pollutants; B, Product; C, Solid Waste.

[a]Expressed as tons of the elemental substance (i.e. Si, Cd, As, Ga) and not a specific compound.

Fig. 1. The primary material balances for different photovoltaic systems, showing the delivery (tons) per 10^{12} Btu of useful energy.

emissions but also decrease risks of environmental harm from toxic materials in solid waste.

5. Environmental pathways to man

Pollutants emitted during the photovoltaic energy cycle may affect man directly through inhalation and ingestion or indirectly through food chains. In this initial study we examine only inhalation routes for three primary materials (*i.e.* arsenic, cadmium and silicon). These specific materials were selected because earlier qualitative assessments suggested that they posed the greatest public health risks for this technology [15 - 17]. Potential effects from other exposure routes and other materials may also be important and are at present being examined.

Estimates of the general public's exposure to primary pollutants from four major activities (mining and milling, refining, fabrication and disposal) were calculated for each cell type. Annual average population exposures within 80 km of each facility were calculated using a gaussian dispersion model which estimates annual average ground level pollutant concentrations [18].

Exposure estimates were made by summing the product of pollution concentration times population to obtain exposure levels (person $\mu g\ m^{-3}$). In this analysis a uniform population distribution of 40 persons km^{-2} was assumed. Actual population densities around these facilities could range from less than 10 to 800 persons km^{-2}. Effects of exposures (person $\mu g\ m^{-3}$) presented would change proportionally in response to these differences.

In Table 3 these results are summarized. Mining and milling activities generally account for the greatest exposures, although these may be over-estimates because of expected differences in particle size deposition rates and chemical form. Effects of refining and fabrication facilities vary in response to control technologies assumed and emission release heights. For the cadmium and arsenic alternatives, refinery exposures exceed fabrication exposures. For the silicon techniques, fabrication exposures appear to be greater than those from the refinery. Exposures are influenced by the quantity of material released, the height of discharge, the distribution of the receptor population and numerous other variables. This analysis serves as a generic example to provide a preliminary assessment.

Neither the quantity of material released nor the chemical form of exposure are known accurately. For the silicon alternative, the chemical might be silicon or SiO_2. Cadmium might be CdO, $CdCl_2$ or CdS. Arsenic exposure might be As_2O_3, As_2O_5, GaAs or other compounds. Actual measurements are not available for most activities and chemicals of interest.

Since arsenic is assumed to have a linear non-threshold health effect (see latter part of Section 6), it was important to estimate exposures beyond the 80 km radius; even though the concentration may be very small, the product of population and concentration may yield large numbers. Using

TABLE 3

Summary of estimated exposures associated with photovoltaic energy cycles

Technology	*Activity*	*Probable pollutant*	*Total population exposure* (person $\mu g\ m^{-3}$)[a]	*Population-weighted average concentration* ($\mu g\ m^{-3}$)	*Exposure histogram* ($\mu g\ m^{-3}$) *for following numbers of persons exposed*					
					$< 10^{-6}$	10^{-6} - 10^{-5}	10^{-5} - 10^{-4}	10^{-4} - 10^{-3}	10^{-3} - 10^{-2}	$> 10^{-2}$
Si n–p	Mine and mill	SiO_2	1.4×10^{2}	1.7×10^{-4}	—	7.1×10^{4}	6.1×10^{5}	6.9×10^{4}	3.2×10^{4}	—
	Refine	Si, SiO_2	8.8×10^{0}	1.1×10^{-5}	—	4.2×10^{5}	3.6×10^{5}	2.0×10^{3}	—	—
	Fabricate	Si	2.1×10^{1}	2.7×10^{-5}	—	2.5×10^{5}	5.0×10^{5}	3.6×10^{4}	—	—
	Dispose[b]	Si, SiO_2	7.5×10^{0}	9.5×10^{-6}	5.6×10^{5}	2.0×10^{5}	3.0×10^{4}	2.0×10^{3}	—	—
Si MIS	Mine and mill	SiO_2	9.8×10^{2}	1.2×10^{-3}	—	—	8.4×10^{4}	6.2×10^{5}	6.1×10^{4}	2.4×10^{4}
	Refine	Si, SiO_2	6.5×10^{1}	8.2×10^{-5}	—	—	6.0×10^{5}	1.9×10^{5}	—	—
	Fabricate	Si	1.5×10^{2}	1.9×10^{-4}	—	—	4.0×10^{5}	3.6×10^{5}	2.4×10^{4}	—
	Dispose[b]	Si, SiO_2	2.7×10^{0}	3.4×10^{-6}	1.8×10^{5}	5.5×10^{5}	3.2×10^{4}	2.4×10^{5}	—	—
CdS	Mine and mill	CdO	3.2×10^{1}	4.1×10^{-5}	—	6.1×10^{5}	1.4×10^{5}	3.2×10^{4}	—	—
	Refine	CdO, $CdCl_2$	2.0×10^{1}	2.5×10^{-5}	—	—	7.6×10^{5}	2.6×10^{4}	—	—
	Fabricate	$CdCl_2$, CdS	1.1×10^{0}	1.4×10^{-6}	5.2×10^{5}	2.4×10^{5}	2.0×10^{4}	—	—	—
	Dispose[b]	CdS, CdO	1.3×10^{-1}	1.7×10^{-7}	7.5×10^{5}	3.2×10^{4}	—	—	—	—
GaAs	Mine and mill	As_2O_3, As_2O_5	9.9×10^{0}	1.3×10^{-5}	8.4×10^{4}	6.2×10^{5}	5.9×10^{4}	2.6×10^{4}	—	—
	Refine	As_2O_3, As_2O_5	8.1×10^{0}	1.0×10^{-6}	—	7.6×10^{5}	2.2×10^{4}	—	—	—
	Fabricate	As_2O_3, As_2O_5	2.8×10^{0}	3.5×10^{-7}	7.5×10^{5}	3.8×10^{4}	—	—	—	—
	Dispose[b]	As_2O_3, As_2O_5	6.3×10^{-3}	8.0×10^{-9}	—	5.8×10^{5}	1.7×10^{5}	3.0×10^{4}	2.0×10^{3}	—

[a] Expressed as micrograms per cubic meter of the elemental substance (*i.e.* silicon, cadmium, arsenic) and not the specific compound.
[b] Exposure estimates are based on 10% release of the elemental substance.

estimates developed by Rowe [19] from a long-range fine particulate transport and dispersion model [20], we calculated the mean U.S. population exposure resulting from arsenic emissions released throughout the photovoltaic energy cycle. Rowe estimated a mean exposure of 2.65×10^{-4} person $\mu g\ m^{-3}$ across the entire country per 10^3 ton of emissions. This value varies by a factor of ± 3 depending on specific source location. Using upper range emission estimates, we calculated a mean U.S. population exposure to arsenic of 2.0×10^{-7} person $\mu g\ m^{-3}$ from a photovoltaic energy cycle capable of 10^{12} Btu output. Here we assumed that all arsenic in the photovoltaic cells is dispersed in the air on disposal. If the photovoltaic cells are not incinerated and no arsenic becomes air borne on disposal, the mean exposure would be 4.4×10^{-8} person $\mu g\ m^{-3}$.

6. Public health

Public health and safety impacts of photovoltaic energy technologies are generally thought to result from pollutants released during steps in the material supply cycle and from pollutants accidentally released during fabrication, operation and disposal of photovoltaic cells. In this initial effort, only the effects of three primary pollutants (*i.e.* arsenic, cadmium and silicon compounds) on public health were explored. On the basis of exposure estimates in Section 5 and detailed reviews of toxicologic data [21 - 24], quantitative and qualitative public health risks of the photovoltaic cycle were estimated. There are other public health risks from photovoltaic energy systems, *e.g.* exposure to sulfur oxides emitted during the refining of structural materials or exposure to leachate from solid waste disposal of photovoltaic fabrication facility byproducts. These risks were not examined in this initial effort.

Although silicon technologies are nearest to commercialization, the prediction of public health risks from possible exposures to silicon is not possible. The toxicology of SiO_2 is well documented [25], but it cannot be assumed to represent the toxic effects of elemental silicon [26]. In contrast, there is extensive information on health effects of arsenic and cadmium compounds from which dose–response functions for renal damage from cadmium and lung cancer from arsenic can be derived.

For cadmium a variety of single- and multiple-compartment models have been proposed to estimate cadmium body burdens [27]. This analysis used a modified version of the single-compartment model developed by Travis and Haddock [28]. The choice of this model was based on two considerations.

(i) Multiple-compartment modeling was overly complex for making gross estimates of aggregate health risks.

(ii) This particular approach was sophisticated enough to incorporate the important effects of age on the various variables.

Using this approach, cadmium burdens in the kidney where cadmium is concentrated were estimated. Using a threshold concept (about 150 -

300 (μg Cd) g^{-1} in the kidney) [29, 30], the numbers of individuals at risk from renal damage can be measured.

Modeling results (Table 4) indicate that direct inhalation of cadmium emitted to the atmosphere during the photovoltaic energy cycle will contribute only a very small increment (less than 2%) of the total kidney burden from all sources. Maximum renal cortex concentrations in the general public from all sources are well below the concentrations (150 - 300 μg g^{-1}) at which renal damage is expected, so the risk of this small incremental exposure is zero.

TABLE 4

Estimated cadmium concentration (μg g^{-1}) in the renal cortex associated with the photovoltaic energy cycle

Source of Cd at peak age	*Cd concentration for the following activities*			
	Mine and mill	*Refinery*	*Fabrication*	*Disposal*
Public				
Age of peak concentration	48	47	47	47
Food	43.36	43.36	43.36	43.36
Ambient air[a]	0.85	0.04	0	0.01
Smoking	10.82	10.82	10.82	10.82
Occupational air	—	—	—	—
Total	55	54	54	54
Occupational				
Age of peak concentration	48	48	48	48
Food	43.36	43.36	43.36	43.36
Ambient air[a]	0.85	0.04	0	0.01
Smoking	10.82	10.82	10.82	10.82
Occupational air[b]	295.53	591.05	147.76	73.88
Total	350	650	200	130

[a] Based on ambient air exposure in the worst sector around each facility.
[b] Based on hypothetical exposures (see text).

Although photovoltaic cells will contain GaAs, very little toxicity information is available for either gallium or GaAs [26]. Therefore, health estimates were based on arsenic for this preliminary analysis. At the exposure levels of interest the principal suspected effect of arsenic is cancer [31 - 35]. The specific dose–response relationship used was developed by the U.S. Environmental Protection Agency Carcinogen Assessment Group [35]. The resulting equation for the standard mortality ratio SMR, *i.e.* the ratio of actual deaths to "expected deaths", is given by

$$\mathrm{SMR} = 1 + \frac{\beta}{\alpha} x$$

where β is the change in the respiratory cancer rate for each increase of

1 (μg As) m^{-3}, α is the base respiratory cancer rate in the absence of atmospheric arsenic and x is the average lifetime exposure to atmospheric arsenic. The two extreme values of 3.3% [31] and 17.0% [32] were used to estimate a reasonable range for β.

Results of the arsenic modeling are shown in Table 5. The analysis suggests that arsenic released during the photovoltaic energy cycle could induce a lung cancer risk of 10^{-8} - 10^{-5} deaths per 100 000 individuals per year within 80 km of photovoltaic-related facilities. If, because of the non-threshold carcinogenic effect assumed for arsenic, exposures beyond 80 km are considered, the calculated effect would still be only 10^{-3} - 10^{-2} deaths per year over the entire U.S. population per 10^{12} Btu installed capacity produced.

Thus potential public health effects from the use of arsenic and cadmium in the photovoltaic energy cycle appear to be small in comparison with other known hazards. Public health risks from silicon exposure cannot be assessed for lack of toxicologic information at this time. Exposure measurements and compilations of basic toxicologic information are required to improve the accuracy of the arsenic and cadmium damage estimates and to assess the risks from silicon exposures.

7. Occupational health: an overview

Chemical and physical hazards in the workplace are the source of occupational health risks, *e.g.* the effect of trauma to a hand or carcinogenic hazard of exposure to arsenic. Occupational risks from chemical hazards were assessed by methods similar to those described for public health. As noted, the toxicology of SiO_2 is well documented and clearly shows that hazards exist in dirty situations such as quartz mining. However, silicosis, commonly suggested as a potential hazard in the photovoltaics industry [16, 18], is entirely preventable; its prevalence in existing industries has declined in the past decade. Exposures to silicon are expected from the different activities examined, but no toxicologic information exists for this material.

Cadmium health effects modeling suggests that chronic exposure in the workplace to levels above 10 μg m^{-3} would produce a total cadmium kidney burden (200 μg g^{-1}) near or exceeding a concentration above which renal damage can be expected (Table 4). Results of arsenic modeling analyses (Table 5) suggest that, if workers were chronically exposed to in-plant arsenic air levels of 10 μg m^{-3}, their cancer rates would be 10% - 50% of the background level for all lung cancers. If workers were exposed to the present threshold limiting value (TLV), significant numbers of cancers could be produced. The TLV, however, is based on a lung damage threshold rather than a cancer end point. Although only limited exposure information is available for many of the activities examined, these hazards should be recognized in the design, production and ultimate commercialization of photovoltaic devices.

TABLE 5

Estimated health effects of arsenic released during the photovoltaic energy cycle (per 10^{12} Btu output)

Health data	*As concentration for the following activities*			
	Mine and mill	*Refinery*	*Fabrication*	*Disposal*
Public (within 80 km)				
Total population	7.8×10^5	7.8×10^5	7.8×10^5	7.8×10^5
Maximum concentration ($\mu g\ m^{-3}$)	4.9×10^{-4}	3.3×10^{-5}	6.0×10^{-6}	1.2×10^{-7}
Total population exposure (person $\mu g\ m^{-3}$)	9.9×10^0	2.8×10^0	2.8×10^{-1}	6.3×10^{-3}
Population-weighted average concentration ($\mu g\ m^{-3}$)	1.3×10^{-5}	3.6×10^{-6}	3.5×10^{-7}	8.0×10^{-9}
Estimated cancer deaths (per year)	$(1.4 - 7.2) \times 10^{-4}$	$(0.40 - 2.1) \times 10^{-4}$	$(0.39 - 2.1) \times 10^{-5}$	$(0.90 - 4.6) \times 10^{-7}$
Cancer death rate (deaths per 100 000 per year)	$(1.8 - 9) \times 10^{-5}$	$(0.51 - 2.7) \times 10^{-5}$	$(0.50 - 2.6) \times 10^{-6}$	$(1.2 - 5.9) \times 10^{-8}$
Occupational				
Total population	8.4×10^{-3}	5.2×10^{-3}	5.7×10^1	5.2×10^{-4}
Maximum concentration ($\mu g\ m^{-3}$)	1.0×10^1	5.0×10^2	1.0×10^1	1.0×10^1
Total population exposure (person $\mu g\ m^{-3}$)	8.4×10^{-2}	2.6×10^0	5.7×10^2	5.2×10^{-3}
Population-weighted average concentration ($\mu g\ m^{-3}$)	1.0×10^1 [a]	5.0×10^2 [a,b]	1.0×10^1 [a]	1.0×10^1 [a]
Estimated cancer deaths (per year)	$(1.2 - 6.1) \times 10^{-6}$	$(0.37 - 1.9) \times 10^{-4}$	$(0.81 - 4.2) \times 10^{-2}$	$(0.74 - 3.8) \times 10^{-7}$
Cancer death rate (deaths per 100 000 per year)	$(1.4 - 7.3) \times 10^1$	$(0.71 - 3.7) \times 10^3$	$(1.4 - 7.3) \times 10^1$	$(1.4 - 7.3) \times 10^1$

[a] Hypothetical exposure.

[b] The exposure estimate is based on the TLV (see text).

Effects of routine occupational accidents in photovoltaic energy cycles are probably similar to those encountered in the day-to-day operation of any industrial plant. By using the Reference Material System described previously, risks from material extraction, processing and refining and from fabrication, installation, operation and decommissioning of the four different photovoltaic devices were examined.

Results of this analysis are shown in Table 6. Details of the calculations and data are described elsewhere [7]. Among the alternatives, there are only small differences in total accident risks. Occupational accidents in fabrication facilities are small compared with those in material supply, installation and operation activities. The relative risk to individual workers at the fabrication facilities (50 worker days lost per 100 man years) is smaller than in competing energy technologies, *e.g.* in coal mining the relative risk to workers is greater than 100 worker days lost per 100 man years. The labor intensiveness of the photovoltaic energy cycle, however, increases the total effect (the risk per worker multiplied by the number of workers) of producing electricity by photovoltaic energy systems.

8. Occupational health: fabrication facilities

Risks to workers in photovoltaic fabrication facilities cannot be measured directly but must be estimated from experience with industries posing similar risks. In a detailed study [36] made as a part of this analysis, risks to workers in four hypothetical fabrication facilities were estimated by (i) describing subprocessing steps within each of the fabrication facilities (*e.g.* crystal growth, ingot processing, junction formation, perimeter grind etc.), (ii) identifying manpower requirements by subprocess and (iii) calculating occupational hazards and risks from actuarial data for the selected subprocesses in related industries (*e.g.* semiconductor).

Table 7 gives the lost workday and fatality estimates at each step in the silicon ingot, silicon ribbon and GaAs fabrication processes. Proprietary claims to information used in estimating labor requirements for the CdS process preclude the breakdown of lost workday and fatality values by process steps.

Lost workdays and fatalities per 100 man years equal about 50 and 0.002 respectively for all technologies. As shown, total lost workdays vary from a minimum of 9.1 for the CdS production process to a maximum of 29.4 for the GaAs alternative. Fatalities show similar patterns varying from a minimum of 3.4×10^{-4} to a maximum of 1.6×10^{-3}. Risks for the four fabrication alternatives increase in the following order: CdS, silicon ribbon, silicon ingot and GaAs. Detailed estimates of lost workday and fatality rates for each process step, summed across each fabrication alternative, are given by Owens *et al.* [36].

The intratechnology assessment reveals that, in the silicon ingot process, crystal growth and ingot processing produce the greatest number of

TABLE 6

Summary of the occupational impacts of photovoltaic energy technologies (per 10^{12} Btu output)

Cell type; activity	*Total labor* ($\times 10^2$ man years)	*Accidents* (worker days lost)	*Fatalities*
Si			
Material supply	6.68×10^{-1}	2.17×10^{2}	1.1×10^{-2}
Fabrication[a]	6.06×10^{-1}	3.03×10^{1}	2.21×10^{-3}
Installation	2.29×10^{0}	2.60×10^{2}	6.88×10^{-2}
Operation	1.50×10^{0}	1.15×10^{2}	3.00×10^{-2}
Decommission	2.27×10^{-2}	2.82×10^{0}	6.80×10^{-4}
Total	5.09×10^{0}	6.25×10^{2}	1.13×10^{-1}
Si MIS			
Material supply	8.82×10^{-1}	3.03×10^{2}	1.5×10^{-2}
Fabrication[a]	5.15×10^{-1}	2.44×10^{1}	2.04×10^{-3}
Installation	3.20×10^{0}	3.62×10^{2}	9.60×10^{-2}
Operation	2.09×10^{0}	1.60×10^{2}	4.19×10^{-2}
Decommission	3.16×10^{-1}	3.93×10^{0}	9.49×10^{-4}
Total	7.01×10^{0}	8.53×10^{2}	1.56×10^{-1}
CdS			
Material supply	9.07×10^{-1}	3.21×10^{2}	1.5×10^{-2}
Fabrication[a]	4.17×10^{-1}	2.14×10^{1}	2.04×10^{-3}
Installation	3.20×10^{0}	3.62×10^{2}	9.60×10^{-2}
Operation	2.09×10^{0}	1.60×10^{2}	4.19×10^{-2}
Decommission	3.16×10^{-2}	3.93×10^{0}	9.49×10^{-4}
Total	6.64×10^{0}	8.68×10^{2}	1.55×10^{-1}
GaAs			
Material supply	6.79×10^{-1}	1.63×10^{1}	1.2×10^{-2}
Fabrication[a]	8.35×10^{-1}	4.17×10^{1}	3.07×10^{-3}
Installation	4.13×10^{-1}	4.67×10^{1}	1.24×10^{-2}
Operation	2.88×10^{-1}	2.20×10^{1}	5.76×10^{-3}
Decommission	4.08×10^{-2}	5.07×10^{-1}	1.22×10^{-4}
Total	2.26×10^{0}	1.27×10^{2}	3.34×10^{-2}

The occupational impact estimates are based on the mortality and morbidity incidence rates at present observed in the normal operation of existing industrial facilities.
[a] Includes fabrication of both collector and other energy-conditioning equipment.

worker days lost and fatalities. Ribbon growth in the silicon ribbon process produces the greatest impacts. In GaAs photocell production, liquid phase epitaxial deposition carries with it the greatest risks. Breakdowns for the CdS process cannot be given.

TABLE 7

Estimated labor requirements, total lost workdays and fatalities associated with a 5.57 MW year^{-1} photovoltaic fabrication plant (per 10^{12} Btu output)

Technologies; process step	*Estimated labor* (employee h)	*Total lost workdays*	*Estimated fatalities*
Si n–p ingot			
Single-crystal Si growth	28470	6.5	3.0×10^{-4}
Ingot processing	23395	5.7	1.4×10^{-4}
Junction formation	1429	0.3	1.6×10^{-5}
Perimeter grind	929	0.2	2.1×10^{-6}
Etching	869	0.3	1.9×10^{-5}
Metallization	1430	0.5	3.3×10^{-5}
Antireflection coating	2503	0.5	2.6×10^{-5}
Cell testing	6794	1.6	8.4×10^{-5}
Interconnection	4034	1.0	4.8×10^{-5}
Encapsulation	5915	1.4	7.2×10^{-5}
Module testing	358	0.1	4.5×10^{-6}
Total	72126	18.1	7.4×10^{-4}
Si MIS ribbon			
Ribbon growth	32596	7.1	3.3×10^{-4}
p^+-Al back contact application	1303	0.3	1.4×10^{-5}
Plasma etching	1983	0.4	2.0×10^{-5}
Ion implantation	1805	0.4	1.9×10^{-5}
Back and front metallization	2607	0.6	3.0×10^{-5}
Antireflection coating	1805	0.4	1.8×10^{-5}
Interconnection	5303	1.3	6.5×10^{-5}
Encapsulation	6105	1.4	7.4×10^{-5}
Module testing	201	0.1	2.8×10^{-6}
Total	53708	12.1	5.7×10^{-4}
GaAs			
Liquid encapsulation Czochralski single-crystal growth	1360	0.3	1.4×10^{-5}
Ingot processing	4777	1.1	2.1×10^{-5}
Liquid phase epitaxial deposition	41658	9.7	4.5×10^{-4}
Deposition of SiO_2 layer	4291	0.9	4.3×10^{-5}
Front metallization	7665	2.1	1.8×10^{-4}
Back metallization	7006	2.4	1.6×10^{-4}
Plate front contacts	894	0.3	2.1×10^{-5}
Removal of the lattice-matching GaAs layer	234	0.1	4.9×10^{-6}
Antireflection coating, plasma deposition	3487	0.8	4.8×10^{-5}
Final cell processing	11443	2.7	1.4×10^{-4}
Module testing	32134	7.3	3.8×10^{-4}
Total	117563	29.4	1.6×10^{-3}

(*continued*)

TABLE 7 *(continued)*

Technologies; process step	*Estimated labor* (employee h)	*Total lost workdays*	*Estimated fatalities*
CdS			
CdS photovoltaic cell and array production	34503	9.1	3.4×10^{-4}
Total	34503	9.1	3.4×10^{-4}

The occupational impact estimates are based on the mortality and morbidity incidence rates at present observed in the normal operation of existing industrial facilities.

9. Conclusion

In this analysis we attempted to develop a consistent framework to estimate crudely the public and occupational health costs of producing electricity via photovoltaic energy technologies. The results suggest that material requirements impose no additional occupational risk to workers, only a reapportionment of the share of existing risks to photovoltaic energy technologies. This apportionment provides a measure against which to compare new risks in fabrication, installation, operation and disposal of the photovoltaic devices. There are potential occupational risks from arsenic and cadmium, but exposure levels in future fabrication facilities are unknown; these issues must be taken into account in developing fabrication alternatives. Similarly, care must be exercised in using cadmium and arsenic but present estimates suggest that public health impacts from the photovoltaic energy cycle for practical purposes are zero. Admittedly, these costs provide only crude estimates of total risk and do not reflect other important factors including the technologies to be commercialized, the control technology employed and the regional effects of future site locations. It is nevertheless hoped that the publication of this paper will foster recognition and discussion in the photovoltaic community about potential health risks of this technology.

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References

1 S. C. Morris, K. N. Novak and L. D. Hamilton, Databook for the quantitation of health effects from coal energy systems, *BNL Rep. 23606 R*, 1979 (Brookhaven National Laboratory, Upton, NY).
2 R. Caputo, An initial comparative assessment of orbital and terrestrial central power systems, *JPL Rep. 900-780*, 1977 (Jet Propulsion Laboratory, Pasadena, CA).
3 H. Inhaber, *Science, 203* (1979) 2718 - 2724.
4 J. P. Holdren, K. R. Smith and G. Morris, *Science, 204* (1979) 564 - 568.
5 H. Inhaber, Risk of energy production, *AECB Rep. 1119/REV-1*, 1978 (Atomic Energy Control Board, Ottawa, Ontario).
6 N. Bhagat (ed.), Reference material systems: a sourcebook for material assessment, *BNL Rep. 50609*, 1976 (Brookhaven National Laboratory, Upton, NY).
7 P. D. Moskowitz, L. D. Hamilton, S. C. Morris, K. M. Novak and M. D. Rowe, Photovoltaic energy technologies: health and environmental effects document, *BNL Rep. 51284*, 1980 (Brookhaven National Laboratory, Upton, NY).
8 R. L. Watts, W. E. Gurwell, C. H. Bloomster, S. A. Smith, T. A. Nelson and W. W. Pawlewicz, Some potential material supply constraints in the deployment of photovoltaic solar electric systems, *PNL Rep. 2971*, 1978 (Pacific Northwest Laboratory, Richland, WA).
9 R. K. Sharma, P. Benioff, M. H. Bhattacharyya, C. D. Brown, M. G. Chasanov, J. R. B. Curtiss, B. Juroslow and R. W. Vocke, Health and environmental effects document for batteries, *ANL Rep. EIS-105*, 1980 (Argonne National Laboratory, Argonne, IL).
10 T. R. Blackwood, S. R. Archer and T. K. Corwin, Status assessment of toxic chemicals — cadmium, *EPA Rep. 600/2-2106*, 1979 (U.S. Environmental Protection Agency, Cincinnati, OH).
11 T. R. Blackwood, D. R. Tierneyand and R. D. Wilson, Status assessment of toxic chemicals — arsenic, *EPA Rep. 600/2-210f*, 1979 (U.S. Environmental Protection Agency, Cincinnati, OH).
12 R. Coleman, Sources of atmospheric cadmium, *EPA Rep. 450/5-006*, 1979 (U.S. Environmental Protection Agency, Research Triangle Park, NC).
13 T. L. Neff, Social cost factors and the development of photovoltaic energy systems, *MIT Rep. EL 79-026*, 1979 (Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA).
14 D. Bickler, in L. Stang, M. Dienes and D. Bohning (eds.), Health effects of photovoltaic technology, *BNL Rep. 51118*, 1980 (Brookhaven National Laboratory, Upton, NY).
15 Solar program assessment: environmental factors, *ERDA Rep. 1713*, 1977 (U.S. Energy Research and Development Administration, Washington, DC).
16 Environmental development plan — photovoltaics, *DOE Rep. EDP-0031*, 1979 (U.S. Department of Energy, Washington, DC).
17 Environmental readiness document — photovoltaics, *DOE Rep. ERD-0008*, 1978 (U.S. Department of Energy, Washington, DC).
18 C. Dopazo, H. N. Lee and P. Michael, Brookhaven National Laboratory long-term gaussian dispersion model, *BNL Rep. 24226*, 1979 (Brookhaven National Laboratory, Upton, NY).
19 M. D. Rowe, Human exposure to particulate emissions from power plants, *BNL Rep. 51305*, 1980 (Brookhaven National Laboratory, Upton, NY).
20 W. J. Eadie and W. E. Davis, The development of a national interregional transport matrix for respirable particulates, *PNL Rep. RAP-37*, 1979 (Pacific Northwest Laboratories, Richland, WA).
21 K. M. Novak, Toxicity of cadmium and its compounds: a review of the literature aimed at identifying dose–response relationships, *BNL Rep.*, in the press (Brookhaven National Laboratory, Upton, NY).
22 K. M. Novak, Toxicity of silicon compounds, *BNL Rep.*, in the press (Brookhaven National Laboratory, Upton, NY).

23 P. G. Green, Toxicity of arsenic and its compounds, *BNL Rep.*, in the press (Brookhaven National Laboratory, Upton, NY).
24 C. V. Robinson and K. M. Novak, Programs and subroutines for calculating cadmium body burdens based on a one-compartment model, *BNL Rep. 51306*, 1980 (Brookhaven National Laboratory, Upton, NY).
25 Department of Health, Education, and Welfare, *Criteria for a Recommended Standard, Occupational Exposure to Crystalline Silica*, U.S. Government Printing Office, Washington, DC, 1974.
26 N. I. Sax, *Dangerous Properties of Industrial Materials*, Van Nostrand–Reinhold, New York, 1979.
27 T. Kjellstrom, K. Shiroishi and P. E. Eurin, *Environ. Res.*, *13* (1977) 318 - 344.
28 C. C. Travis and A. G. Haddock, *Environ. Res.*, *22* (1980) 46 - 60.
29 L. Friberg, M. Piscator, G. F. Nordberg and T. Kjellstrom, *Cadmium in the Environment*, CRC Press, Cleveland, OH, 2nd edn., 1974.
30 R. R. Lauwerys, *Criteria (Dose/Effect Relationships) for Cadmium*, Commission of European Communities, Pergamon, Oxford, 1978.
31 A. M. Lee and J. F. Fraumeni, *J. Natl. Cancer Inst.*, *42* (1969) 1045 - 1052.
32 M. G. Ott, B. J. Holder and L. H. Gordon, *Arch. Environ. Health*, *29* (1974) 250 - 255.
33 S. Minkowitz, *Ann. Intern. Med.*, *61* (1964) 296 - 299.
34 G. Pershagen and M. Vahter, Arsenic, a toxicological and epidemiological appraisal, *Rep. SNV PM-1128*, 1978 (Swedish Environmental Protection Board, Libertryck, Stockholm).
35 P. Mushak, W. Galke, U. Hasselbald and L. Grant, Health assessment document for arsenic, *EPA Rep.*, 1980 (U.S. Environmental Protection Agency, Research Triangle Park, NC).
36 T. Owens, L. Ungers and T. Briggs, Estimates of occupational safety and health impacts resulting from large-scale production of major photovoltaic technologies, *BNL Rep. 51324*, 1980 (Brookhaven National Laboratory, Upton, NY).