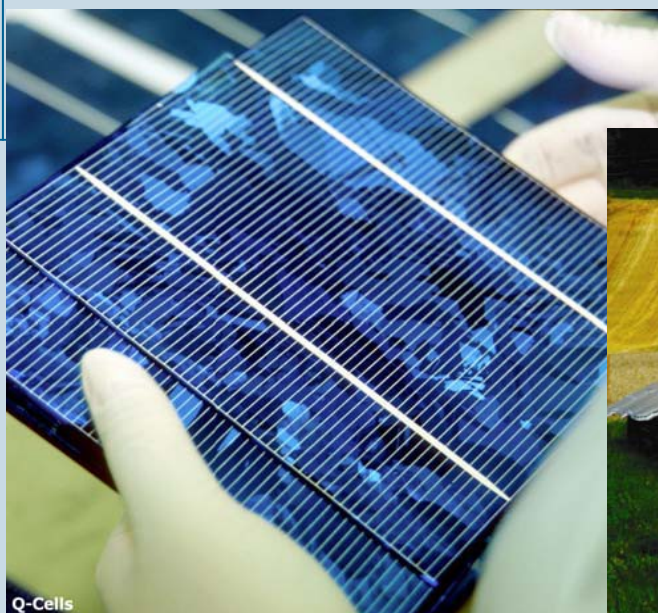




Human health risk assessment methods for PV Part 1: Fire risks



PVPS

PHOTOVOLTAIC
POWER SYSTEMS
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PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Human health risk assessment methods for PV

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Appendix A. Evaluation of Potential Impacts to Soil and Groundwater

List of Units

cal/s – calories per second

g – grams

g/s – grams per second

hr – hour

kg/L – kilograms per liter

kJ/s – kilojoules per second

kW – kilowatts

L – liters

L/kg – liters per kilogram

m – meter

m/s – meters per second

m² – square meters

mg – milligrams

mg/L – milligrams per liter

mg/kg – milligrams per kilogram

µg/m³ – micrograms per cubic meter

Executive Summary

The photovoltaic (PV) industry has experienced rapid growth in recent years due in part to the development of public policies to address climate change and energy security. Some industry stakeholders have expressed concerns regarding potential human inhalation exposure to hazardous materials should a PV module array be exposed to fire, particularly in a residential or commercial rooftop application. To evaluate these concerns, fire hazard analysis methods are presented that can estimate emissions that may occur when PV modules (hereafter mostly referred to simply as “modules”) are exposed to fire, estimate the associated chemical concentrations in ambient air downwind from the fire, and finally compare these exposure-point concentrations to health-protective screening levels.

Specifically, this report presents an analysis of potential human health impacts associated with chemical release from modules during a building fire for three PV technologies, focusing on airborne release of the highest-prioritized chemical element for each: Pb content in crystalline-silicon (c-Si) modules, Cd content in thin film cadmium telluride (CdTe) modules, and Se content in thin film copper indium selenide (CIS) modules. The intent of this analysis is to demonstrate the application of the proposed methods for modules exposed to fire in a quantitative yet illustrative manner. In particular, this report quantifies what are expected to be the worst-case potential health impacts over a wide range of possible conditions, including building/fire size, downwind receptor location, exposure duration, and meteorological conditions, utilizing a Gaussian plume modeling approach that is typically used in regulatory contexts.

The proposed method follows a screening-level approach, with the intent of developing order of magnitude-level estimates of potential risk after applying health-protective assumptions. Three scenarios are considered: a small, medium, and large building fire. A small building fire may involve fewer modules and thus a lower mass of chemical released than a medium or large building fire. However, as compared to a large building fire, a small building fire may produce less atmospheric dispersion of the released chemical and thus higher air pollutant concentrations, due to lower heat release. To evaluate these competing effects, three sizes of module array/building fire are analyzed here: a “small” building with module area of 100 m², a “medium” building with module area of 2,500 m², and a “large” building with module area of 10,000 m².

The emissions from c-Si, CdTe, and CIS PV modules under each of the three sizes of fire conditions are estimated on the basis of the total mass of chemical contained in the modules and release-efficiency data measured by BMWi, TÜV Rheinland, and Fraunhofer ISE, who together conducted a study on different PV technologies in which modules were subjected to flames from the underside of the module by means of a gas burner. In that study, measured concentrations in the flue gas, and in the water used to extinguish the fire, were used to estimate release-efficiency of specific chemical constituents to air and water, respectively.

The chemical concentrations in ambient air resulting from release from fire-exposed modules are estimated using the United States Environmental Protection Agency (USEPA) Gaussian plume dispersion model SCREEN3. Small, medium, and large building fires are all evaluated to determine worst-case potential impacts. Use of the SCREEN3 model for this purpose is consistent with USEPA guidance. The modeling approach is designed to quantify worst-case potential impacts at any receptor location downwind from the edge of the burning building across a range of potential fire scenarios. Building downwash model options in SCREEN3 are employed. For each type of building fire, worst-case concentrations are estimated for averaging times of 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours, corresponding to potential

exposure times under different ground-level exposure scenarios (neighborhood and general public) at downwind distances ranging from 5 to 1,000 m for a small building fire and 25 to 10,000 m for a medium or large building fire.

The potential health effects associated with short-term (acute) inhalation exposures are evaluated through a comparison of predicted exposure-point concentrations with Acute Exposure Guidelines (AEGL) published by the USEPA and Protective Action Criteria (PAC) published by the United States Department of Energy (USDOE). AEGL screening values are preferentially used when available based on more extensive review of animal and human studies, but since AEGLs are not set for all chemicals, PAC screening values can fill gaps. The AEGL and PAC represent threshold exposure limits for the general public and are applicable to acute exposure periods ranging from 10 minutes to 8 hours. Three levels of screening values (AEGL-1/PAC-1, AEGL-2/PAC-2, and AEGL-3/PAC-3) are in increasing order of severity of effects, with the AEGL-2 or PAC-2 criteria used by USEPA or USDOE to determine whether there is a disabling risk to potential receptors. Our modeling results suggest that for the small, medium, and large building fires considered, potential Pb, Cd, and Se concentrations from c-Si, CdTe, and CIS PV, respectively are below AEGL-2/PAC-2 thresholds, and also below AEGL-1/PAC-1 and AEGL-3/PAC-3 thresholds, for all averaging times (10 minutes to 8 hours).

The potential incremental cancer risk associated with one-time, acute inhalation exposure (for 10 minute averaging time which produces the highest product of concentration and duration) is quantified in accordance with USEPA inhalation risk assessment methodology. This approach is conservative; it is uncertain whether short-term exposures as a result of a fire would increase an individual's lifetime probability of developing cancer, as cancer studies are based on long-term exposures. We find that under the examined scenarios, the incremental cancer risks associated with inhalation of Pb and Cd potentially released from photovoltaic modules in small, medium, and large building fires are less than the 1×10^{-6} (one in a million), which is typically considered to be a negligible risk level by regulatory agencies, such as the USEPA. Incremental cancer risks associated with inhalation of Se potentially released from photovoltaic modules are not evaluated because Se is not classified as a carcinogen.

Potential indirect impacts associated with each fire scenario are also considered. Extinguishing the fire with water may result in chemical transport to soil and/or groundwater. The water-borne transport pathway has been evaluated, with exposure-point concentrations of Pb, Cd, and Se for c-Si, CdTe, and CIS PV, respectively, below risk-based screening levels and maximum contaminant levels from USEPA (Appendix A).

In this report, only three chemicals (Pb, Cd, Se) have been used to demonstrate the human health risk assessment methodology for three types of PV modules exposed to fire, whereas other environmentally sensitive elements (e.g., In, Ag, Cu, Sn, Ni) are used in commercial PV modules and new PV technologies that (e.g., perovskite) are emerging. Thus the results presented here do not represent a complete human health risk assessment for fire-exposed modules, although the results are suggestive of low risk for the prioritized chemicals examined. The screening-level methods employed in this report can be used to assess potential health risks from other chemicals of potential concern and other PV technologies to establish a more complete set of results for chemicals of potential concern. Screening-level human health risk assessment has been conducted for potential ground-level receptors (neighborhood and general public), but not for potential occupational exposures to firefighters, which may be evaluated separately using occupational health screening values and accounting for occupational exposure factors. Potential ecological risks have also not been evaluated in this report. Screening-level methods such as used here are meant to identify potential health risk scenarios that are greater than defined thresholds and may warrant further analysis.

Foreword

The IEA PVPS is one of the collaborative R&D Agreements established within the IEA, and was established in 1993. The overall programme is headed by an Executive Committee composed of representatives from each participating country and/or organisation, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. The programme deals with the relevant applications of photovoltaics, both for on-grid and off-grid markets. It operates in a task-shared mode whereby member countries and/or organisations contribute with their experts to the different Tasks. The co-operation deals with both technical and non-technical issues relevant to a wide-spread use of photovoltaics in these different market segments.

The mission of the IEA PVPS programme is: “To enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.” The underlying assumption is that the market for PV systems is rapidly expanding to significant penetrations in grid-connected markets in an increasing number of countries, connected to both the distribution network and the central transmission network. At the same time, the market is gradually shifting from a policy to a business driven approach.

Task 12 aims at fostering international collaboration in safety and sustainability that are crucial for assuring that PV grows to levels enabling it to make a major contribution to the needs of the member countries and the world.

The overall objectives of Task 12 are to:

1. quantify the environmental profile of PV electricity, serving to improve the sustainability of the supply chain and to compare it with the environmental profile of electricity produced with other energy technologies;
2. help improve waste management of PV in collection and recycling, including tracking legislative developments as well as supporting development of technical standards;
3. distinguish and address actual and perceived issues associated with the EH&S, social and socio-economic aspects of PV technology that are important for market growth; and
4. disseminate the results of the EH&S analyses to stakeholders, policy-makers, and the general public.

The first objective is served with Life Cycle Assessment (LCA) that describes energy, material and emission flows in all stages of the life cycle of PV, as well as human health risk assessment.

The second objective is accomplished by proactive research and support of industry-wide activities (e.g., input to Industry Associations, like SolarPower Europe or Industry standardization activities to develop and help implementing voluntary or binding policies – like EU WEEE and the Product Environmental Footprint Category Rules for photovoltaics in Europe and the development of a Sustainability Leadership Standard for Photovoltaic Modules (NSF 457).

The third objective is addressed by advocating best sustainability practices throughout the solar value chain, exploring and evaluating frameworks and approaches for the environmental, social and socio-economic assessment of the manufacturing, installation and deployment of PV technologies and thus assisting the collective action of PV companies in this area.

The fourth objective is accomplished by presentations to broad audiences, peer review articles, reports and fact sheets, and assisting industry associations and the media in the dissemination of the information.

Task 12 was initiated by Brookhaven National Laboratory under the auspices of the U.S. Department of Energy and is now operated jointly by the National Renewable Energy Laboratory (NREL) and Solar Power Europe. Support from DOE and Solar Power Europe are gratefully acknowledged. Further information on the activities and results of the Task can be found at: <http://www.iea-pvps.org>.

This report addresses the third objective above by describing methods to assess potential health impacts should a PV module be exposed to fire. This report is part 1 of a three-part series on human health risk assessment methods for PV. Part 2 will address potential health risks resulting from module breakage and Part 3 will address potential health risks resulting from module disposal. A related report addressing firefighter safety can be found at the IEA PVPS web site: "Photovoltaics and Firefighters' Operations: Best Practices in Selected Countries."

1. Introduction

Potential human health effects related to smoke from building fires include asphyxiation (due to hypoxia from exposure to carbon monoxide, hydrogen cyanide, or oxygen-depleted air) and respiratory effects (due to irritants such as halogen acids, partially oxidized organic compounds, nitrogen oxides, sulfur dioxide, and aerosols) [1]. In the case of building fires involving PV modules, potentially there are additional hazards from off-gassing of fire-affected modules. In this report, methods are presented to estimate potential human health impacts for ground-level receptors downwind of a building fire involving rooftop PV modules. For further background on potential hazards to firefighters, mitigation measures, and best practices for fire prevention, readers are encouraged to consult a recent report by the International Energy Agency [2].

Fire events involving PV modules are relatively rare. For example in Germany, a total of 430 fire events out of 1.3 million PV installations had been reported as of 2013 [3]. Some industry stakeholders have expressed concerns regarding potential exposures to hazardous materials should a PV array be exposed to fire, particularly in a residential or commercial rooftop application. To evaluate these concerns, human health risk assessment methods are presented herein to estimate emissions that may occur when PV modules are exposed to fire, estimate the associated chemical concentrations in ambient air downwind from the fire, and compare these exposure point concentrations to risk-based screening levels.

A paradigm for human health risk assessment was first developed by the U.S. National Academy of Sciences and consists of four main steps of: hazard identification, dose-response assessment, exposure analysis, and risk characterization [4]. With regard to hazard identification, while a variety of chemicals (asphyxiant, corrosive, irritating, flammable or explosive, hazardous) are used in the manufacturing of PV modules [5], the highest-prioritized chemical element from three PV technologies are evaluated in this report as illustrative examples of the application of the methods developed herein. Dose-response assessment is incorporated in the use of health screening values for non-cancer hazards (section 7.1) and inhalation unit risk factors for cancer risks (section 7.2). Exposure analysis includes the characterization of chemical emissions (section 3) and environmental fate of emissions (sections 4-6). Risk characterization and associated uncertainties are covered in sections 7-8.

Screening-level human health risk assessment methods, based on the above paradigm but specific to PV, have been outlined by the International Electrotechnical Commission [5] and Bavarian Environmental Protection Agency [6], utilizing VDI Guideline 3783 Sheet I [7]. These PV-specific methods are followed and expanded upon in this report using example cases of evaluating potential human health risks from a single, prioritized chemical from each of three PV technologies: Pb content in crystalline-silicon (c-Si) PV, Cd content in thin film cadmium telluride (CdTe) PV, and Se content in thin film copper indium selenide (CIS) PV. In addition to these metals, other potential chemicals of concern are emissions of carbon monoxide (CO), formaldehyde (CH₂O), and hydrogen fluoride (HF) from combustion of organic PV module materials (encapsulant and backsheet) [3]. While the latter emissions are not considered here, they could be evaluated with the same methodology as presented for Pb, Cd, and Se.

Methods are presented for rooftop PV systems due to the higher potential fire temperatures and proximity to potential receptors associated with building fires compared with ground mount PV systems [8][9]. Potential indirect impacts associated with the fire scenario have also been considered. Extinguishing the fire with water may result in transport of particulates to soil and/or groundwater. This

water-borne transport pathway is considered via a screening level analysis in Appendix A, whose results are summarized in section 9 below.

2. Overview

The objective of this screening-level fire risk assessment is to illustratively demonstrate methods for assessing reasonable worst-case potential inhalation impacts associated with release of prioritized hazardous substances from modules during a fire, over a range of potential conditions, identified in the bullets below. In selecting the exposure scenarios and key parameters, the analysis is intended to be conservative, with the overall objective of not underestimating the potential emissions that could result from a fire affecting rooftop-mounted PV modules on buildings of three sizes: small, medium, and large.

- Module array size. A small building fire may involve fewer PV modules and thus a lower mass released, but may produce less atmospheric dispersion of the released mass and thus higher concentrations in the air, due to lower heat release, compared to a larger building fire. To evaluate these competing effects, three sizes of module array/building fire are analyzed here: a “small” building with module area of 100 m², a “medium” building with module area of 2,500 m², and a “large” building with module area of 10,000 m².
- Dispersion modeling approach. In this analysis, the dispersion of emissions from a building fire is modeled using the United States Environmental Protection Agency (USEPA) Gaussian plume dispersion model, SCREEN3, with “flare” (point-source combustion) source type.
- Duration of exposure event. The shorter the period over which the fire emissions are assumed to occur, the higher the predicted worst-case concentration in ambient air. This effect is caused by two factors. First, it is conservatively assumed that all of the emissions from modules in a fire are released during the exposure period, whereas in actuality, the emissions may take longer to occur. Consequently, as the exposure period decreases, the assumed emission rate increases, given a fixed mass of emissions. Second, the predicted concentrations in ambient air resulting from these emissions increase as the exposure time decreases, because the expected atmospheric dispersion of emissions increases with time. On the other hand, the concentration to which a person would need to be exposed before experiencing adverse acute health effects also increases with decreasing exposure time, due to a shorter duration of exposure. To account for this effect, different acute regulatory concentration levels of concern have been established for the following exposure periods: 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours. Thus, as the exposure time decreases, both the predicted concentration and the risk-based concentration of concern (*i.e.*, the screening level) increase. Yet they vary at different rates, which means that determining the most conservative acute regulatory level of concern is not possible without evaluating a range of exposure times. Accordingly, all of the aforementioned exposure periods are considered in this methodology.
- Meteorological conditions. The downfield dispersion of emissions from a fire are strongly influenced by meteorological conditions. In this analysis, a variety of meteorological conditions (*e.g.*, combinations of wind speed and atmospheric stability) are considered, to identify worst-case potential impacts.

- Building downwash. Air movement over a building can generate eddies on the downwind side of the building that draw near-building plumes downward – this phenomenon is known as building downwash. Building downwash is a function of building dimensions, plume release height, plume rise, wind speed, and plume proximity to the building. The evaluation of potential building downwash effects including cavity recirculation and building wake effects has been incorporated into this methodology.

This fire hazard analysis quantifies worst-case potential impacts over a wide range of possible conditions. As described in detail in Sections 3 through 7, the analysis is comprised of the following sequential steps.

- Section 3 - The input factors for calculation of mass emission rate (g/s) from the building fire are determined, based on the amount of material present in the module array and the release efficiency from modules in a building fire [3]. The heat release rate from the fire (cal/s) is also estimated on the basis of the building/array size. As noted above, three sizes of building/array are evaluated.
- Section 4 - The SCREEN3 model is run to simulate the downfield dispersion of emissions from each building fire. The model is run with a unit source strength (*i.e.*, mass emission rate) of 1 g/s. The model output parameter of interest is the highest predicted 1-hour average concentration ($\mu\text{g}/\text{m}^3$ per g/s) at any distance downwind and at a receptor height of 1 m above the ground surface [6]. This modeled concentration can be considered to be normalized by the emission rate, and is so named “normalized concentration” for the purposes of this report. These 1-hour average concentrations are related to other averaging times (10 mins to 8 hrs) using persistence factors, as described in Section 5.
- Section 5 - SCREEN3 only estimates the maximum 1-hour average concentration – frequently, as is the case here, one would like to know the maximum concentration associated with a different averaging time. As the averaging time changes, the degree of dispersion affecting the estimated pollutant concentration also changes. The effect of this change in dispersion on estimated concentration has been summarized in a series of empirical persistence factors developed by the USEPA that relate the concentration estimated using one averaging time to the concentration predicted using a different averaging time [12][13]. Accordingly, persistence factors are applied to the predicted worst-case 1-hour normalized concentration, to estimate worst-case normalized concentrations in air over other time periods of interest.
- Section 6 - The worst-cased modeled normalized concentrations are combined with the estimated mass emission rate to calculate worst-case concentrations in ambient air ($\mu\text{g}/\text{m}^3$) over the averaging time (also referred to as “exposure period” in this study).
- Section 7 - Finally, the potential for short-term exposures that could occur as a result of an accidental fire to result in adverse health effects to sensitive individuals within a population is evaluated in this screening-level fire hazard analysis. Potential adverse health effects are evaluated in two categories, in accordance with USEPA inhalation risk assessment methodology [14]: acute non-cancer health effects, and carcinogenic health effects.
 - Section 7.1 - The potential for acute non-cancer health effects are evaluated by comparing worst-case concentrations in ambient air to Acute Exposure Guidelines (AEGs) published by USEPA [15] and to Protective Action Criteria (PAC) published by USDOE [16], where AEGs are not available.

- Section 7.2 - The potential for one-time, acute exposures to result in an increased probability of developing cancer over the course of a lifetime is estimated using USEPA risk assessment methodology [14], although it is important to note that there is significant uncertainty as to whether a one-time acute exposure could actually ever result in an increased risk of developing cancer. USEPA cancer risk assessment guidance is based on an assumption that exposure occurs over a chronic (long-term) period. Nonetheless, as a conservative screen, the long-term chronic cancer risk assessment methodology recommended by USEPA is used here to estimate the potential for increased probability of developing cancer as a result of an acute, one-time exposure that could occur from an accidental fire.

These steps are described in more detail in Sections 3 through 7. A discussion of the uncertainties in this evaluation is provided in Section 8.

3. Mass Emission Rates

Researchers have attempted to quantify the mass emissions of hazardous materials that could be released from modules during a fire by conducting fire experiments on modules or pieces of modules. Brookhaven National Laboratory (BNL) measured Cd emissions from CdTe PV module pieces in a tube furnace [8], while Centre Scientifique et Technique du Bâtiment and Institut National de l'Environnement Industriel et des Risques (CSTB/INERIS) and Fraunhofer Informationszentrum Raum und Bau and Bundesanstalt für Materialforschung und -prüfung (Fraunhofer IRB/BAM) utilized fire flames applied to PV modules with heat flux measured by calorimetry [10][11]. Both CSTB/INERIS and Fraunhofer IRB/BAM measured emissions of common substances in smoke such as carbon monoxide, nitrogen oxides, volatile organic compounds, and halogen acids. In addition, Fraunhofer IRB/BAM measured metal emissions from CdTe and CIGS PV modules. The most recent and comprehensive contribution to the investigation of emissions in case of fire involving PV modules was undertaken by TÜV Rheinland and Fraunhofer ISE [3] funded by the German Bundesministerium fuer Wirtschaft und Technologie (BMWi). In this study, fire tests were applied to all major commercial PV technologies (crystalline Si, CdTe, and CIS modules) in the Fire Research Laboratories of CURRENTA in June 2014, and the release of hazardous substances to the air from the burning of PV modules and to water from extinguishing the burning PV modules was characterized. For metals, emissions can be in the form of the metal and/or its oxide, but test results only present the metal content.

The modules mounted on a tilted structure (23°), were exposed to fire flames from the underside by means of a gas burner to simulate a potential rooftop fire scenario. The modules were exposed to fire intensities of 25 and 150 kW (25 and 150 kJ/s), in order to simulate hazardous substance release under different thermal conditions. In addition, a third experiment was conducted using a 150 kW (150 kJ/s) gas burner, in which fire was extinguished after 6 to 7 minutes using 20 liters of water over a period of 45 s. In all the cases, the concentration of hazardous substances present in the flue gas and the fire residues was analyzed. In the case where water was used to extinguish the fire, concentrations of these substances in the water after extinguishing the fire were also analyzed. The CURRENTA results from the 150 kW burner with water spray test are used in this report because they provide data for both emissions to air and water. For emissions of Pb from c-Si PV modules and Cd from CdTe PV modules, total mass of emissions to air were higher than emissions to water, but for Se from CIS PV modules, the total mass of emissions to air and water were comparable.

According to the data provided in the CURRENTA study of emissions to air of 29 mg Cd per CdTe PV module and based on 6 g of total Cd content per module (Table 1), the percentage of Cd emissions to air is 0.5%, which is consistent with earlier results from BNL of 0.5% [8]. For reference, the maximum mass of Cd emitted from a CdTe PV module in the Fraunhofer IRB/BAM study was 12 mg [11], comparable to and lower than the CURRENTA study. The percentage of Pb emissions to air from c-Si PV modules in the CURRENTA study is 4.6% based on emissions to air of 600 mg Pb per c-Si PV module in the CURRENTA study and based on 13 g of total Pb content per module (Table 1). The percentage of Se emissions to air from CIS PV modules is 0.1% based on emissions to air of 4.8 mg Se per CIS PV module in the CURRENTA study and based on 5 g of Se content per module (Table 1). For reference, the maximum mass of Se emitted from a CIGS PV module in the Fraunhofer IRB/BAM study was 6 mg [11], similar to the CURRENTA study. Emissions are modeled from a “small” fire with rooftop area (and module area) of 100 m², a “medium” building fire with rooftop and module area of 2,500 m², and a “large” building fire with rooftop and module area of 10,000 m² (Table 1). While the rooftop area is assumed to be completely covered with PV modules, in actuality, the roof may be only partially covered. The assumptions in Table 1 can be adjusted for site-specific analysis.

Table 1. Input factors for calculation of mass emission rate (Eq. 1)

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
c-Si PV					
Mass of Pb content per module (M)	13	13	13	g/module	Based on 60 cell c-Si PV module*
Module width	1.00	1.00	1.00	m	
Module length	1.60	1.60	1.60	m	
Module area	1.6	1.6	1.6	m ²	
Rooftop width	10	50	100	m	Assumption
Rooftop length	10	50	100	m	
Rooftop area	100	2,500	10,000	m ²	
Number of modules on rooftop (N)	63	1,563	6,250	module	Rooftop area ÷ Module area
Release efficiency in flue gas (RE)	4.6%	4.6%	4.6%	–	Based on [3], see text
CdTe PV					
Mass of Cd content per module (M)	6	6	6	g/module	[17]
Module width	0.60	0.60	0.60	m	
Module length	1.20	1.20	1.20	m	

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
Module area	0.72	0.72	0.72	m ²	
Rooftop width	10	50	100	m	Assumption
Rooftop length	10	50	100	m	
Rooftop area	100	2,500	10,000	m ²	
Number of modules on rooftop (N)	139	3,472	13,889	module	Rooftop area ÷ Module area
Release efficiency in flue gas (RE)	0.5%	0.5%	0.5%	–	Based on [3], see text
CIS PV					
Mass of Se content per module (M)	5	5	5	g/module	[18] assumed equal to c-Si PV modules size
Module width	1.00	1.00	1.00	m	
Module length	1.20	1.20	1.20	m	
Module area	1.2	1.2	1.2	m ²	
Rooftop width	10	50	100	m	Assumption
Rooftop length	10	50	100	m	
Rooftop area	100	2,500	10,000	m ²	
Number of modules on rooftop (N)	83	2,083	8,333	module	Rooftop area ÷ Module area
Release efficiency in flue gas (RE)	0.1%	0.1%	0.1%	–	Based on [3], see text

* Mass of Pb content per c-Si module based on 60 cell module and 0.22 gram Pb per cell assuming 156 mm cell, 3 busbars (front and back cell) and Sn63Pb37 solder [19].

4. Dispersion Modeling

The concentrations in ambient air, resulting from burning of modules during a building fire, are estimated using the USEPA-approved Gaussian plume dispersion model SCREEN3 [20]. Small, medium, and large building fires are all evaluated, to determine worst-case potential impacts. Use of the SCREEN3 model for this purpose is consistent with USEPA guidance [21], which recommends that chemical release from a burning pool of liquid or from a burning pile of tires be modeled with TSCREEN [22] as a gaseous release from a flare point source; and is consistent with industry practice [23]. Fire plume behavior is assumed to be similar between a burning building and a burning pool or a burning pile

of tires. TSCREEN uses a variety of air dispersion models (SCREEN3, PUFF, and RVD) to evaluate different types of releases. For the burning pool and burning pile of tires scenarios, TSCREEN uses a version of SCREEN3 to evaluate plume dispersion. Therefore, SCREEN3 is used in this report as well.

Key model input parameters are discussed below. Overall, the modeling approach is designed to quantify worst-case potential impacts at any ground-level receptor location downwind from the edge of the burning building across a range of potential fire scenarios (small, medium, and large building fires). Building downwash model options are employed to consider eddies on the downwind side of the building that may draw near-building plumes downward, potentially impacting ground-level receptors. Building height and flare stack height (4 m and 5 m, respectively) assume a one-story building, as this will result in the greatest impact to downwind ground-level receptors. The model allows the user to specify urban or rural land use in the vicinity of the emissions source. The more conservative option, rural land use, is used in all model runs in this assessment.

- Source type. As noted above, the small, medium, and large building fires are modeled as point flare sources. Modeling an area/volume source (e.g., building fire) as a point source is conservative, as this assumption neglects the initial dilution provided by air which is drawn in over the source [21].
- Emission rate. A unit emission rate of 1 g/s is used in all model runs. The concentrations predicted by the model are therefore considered “normalized” concentrations ($\mu\text{g}/\text{m}^3$ per g/s). Model predictions are later scaled by the actual emission rates, to estimate downwind concentrations ($\mu\text{g}/\text{m}^3$).
- Total heat release rate. This input parameter influences the initial plume rise; a higher value produces more plume rise, greater dispersion, and therefore lower concentrations. The heat release rates (cal/s) from small residential and large commercial fires are estimated by assuming a low heat flux of 50 kW/m² [24] from each type of fire (small, medium, and large building fires); the heat release rates (cal/s) are then calculated by multiplying this assumed heat flux by the area of modules burned (Table 2). Given higher heat flux, the actual plume rise and dispersion downwind from building fires would be greater than estimated here.
- Meteorological conditions. As indicated in Table 3, a “1 (full)” variety of meteorological conditions (e.g., combinations of wind speed and atmospheric stability) are considered to identify worst-case potential impacts. SCREEN3 uses Pasquill-Gifford stability classes representing six levels of atmospheric stability (1 – very unstable; 2 – unstable; 3 – slightly unstable; 4 – neutral; 5 – slightly stable; 6 – stable). The specific combination of wind speed and stability class resulting in maximum downwind concentration is shown in the “Results” section of Table 3.

Table 2. Calculation of heat release rates applicable to all PV module types

Parameter	Small Building	Medium Building	Large Building	Units	Notes
Heat flux	50	50	50	kW/m ²	[24]
Rooftop area	100	2,500	10,000	m ²	See Table 1
Heat release rate	5.00E+06	1.25E+08	5.00E+08	J/s	Multiplication
Heat release rate	1.20E+06	2.99E+07	1.20E+08	cal/s	Units conversion

The output parameter from the SCREEN3 model is the worst-case 1-hour average normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s), after accounting for a range of possible meteorological conditions as described above, a range of downwind distances (Table 3), and modeling options such as building downwash as described above. Modeling inputs and results are summarized in Table 3.

Table 3. Summary of SCREEN3 Input Data* and Results

		Small Building Fire	Medium Building Fire	Large Building Fire
Parameter	Units			
<i>Input Data</i>				
Run title	–	S_1	M_1	L_1
Source Type	–	F (flare)	F (flare)	F (flare)
Mixing height option	–	(not used)	(not used)	(not used)
Non-default anemometer height	–	(not used)	(not used)	(not used)
Non-regulatory cavity calculation	–	(not used)	(not used)	(not used)
Emission rate	g/s	1	1	1
Flare stack height	m	5	5	5
Total heat release rate	cal/s	1.20E+06	2.99E+07	1.20E+08
Receptor height above ground	m	1	1	1
Urban/rural option	–	R (rural)	R (rural)	R (rural)
Consider building downwash?	–	Y (yes)	Y (yes)	Y (yes)
Building height	m	4	4	4
Minimum horizontal building dimension	m	10	50	100
Maximum horizontal building dimension	m	10	50	100
Use complex terrain screen for terrain above stack height?	–	N (no)	N (no)	N (no)
Use simple terrain screen with terrain above stack base?	–	N (no)	N (no)	N (no)

		Small Building Fire	Medium Building Fire	Large Building Fire
Parameter	Units			
Choice of meteorology	–	1 (full)	1 (full)	1 (full)
Automated distance array?	–	Y (yes)	Y (yes)	Y (yes)
Minimum distance	m	5	25	50
Maximum distance	m	1000	10000	10000
Use discrete distances?	–	N (no)	N (no)	N (no)
Fumigation calculation?	–	NA	NA	NA
Consider shoreline fumigation?	–	NA	NA	NA
Distance to shoreline	m	NA	NA	NA
<i>Results</i>				
Maximum 1-hr normalized concentration	$\mu\text{g}/\text{m}^3$ per g/s	9.60E+01	7.43E-01	2.73E-01
Distance from source to maximum 1-hr normalized concentration	m	40	1180	1436
Meteorological Stability Class		4 (Neutral)	1 (Very unstable)	1 (Very unstable)
Wind speed at 10 m	m/s	20.0	2.0	3.0

*(not used)" indicates optional case-specific meteorological modeling parameters not utilized in this study

5. Persistence Factors

The output parameter from the SCREEN3 model is the worst-case 1-hour average normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s). This 1-hour result is multiplied by persistence factors to estimate worst-case normalized concentrations over averaging times other than 1 hour. Specifically, for comparison of a predicted concentrations to acute risk-based screening levels (see Sections 6.0 and 7.0), worst-case normalized concentrations are estimated for averaging times of 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours (inhalation exposures are assumed to occur over each of these specific durations). The persistence factors used in this analysis are published by USEPA [12][13]. Persistence factors, and the resulting worst-case normalized concentrations, over the various averaging times are documented in Table 4 (small building fire), Table 5 (medium building fire), and Table 6 (large building fire).

6. Exposure Point Concentrations

Maximum concentrations (MC; $\mu\text{g}/\text{m}^3$) in ambient air downwind from small, medium, and large building fires, resulting from emissions from burning modules, are estimated by combining the maximum normalized concentrations (MNC; $\mu\text{g}/\text{m}^3$ per g/s) with the estimated emission rates (ER; g/s) for different averaging times (AT; s):

$$MC = MNC \times ER \quad (\text{Eq. 1})$$

$$MNC = MHNC \times PF \quad (\text{Eq. 2})$$

$$ER = \frac{M \times N \times RE}{AT} \quad (\text{Eq. 3})$$

where M is the mass (g) of chemical content per module, N is the number of modules on rooftop, and RE is the release efficiency (%) in the flue gas (Table 1), and MHNC is the maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s) (Table 3) and PF is the persistence factor (PF; unitless) (Table 4).

For each type of building fire, worst-case concentrations are estimated for averaging times of 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours, and are compared to acute risk-based screening levels developed for these same exposure intervals (see Section 7). These calculations are documented in Table 4 (small building fire), Table 5 (medium building fire), and Table 6 (large building fire).

For the small building fire, worst-case concentrations in air range from 0.004 $\mu\text{g}/\text{m}^3$ (8-hour average) to 9 $\mu\text{g}/\text{m}^3$ (10-minute average) for Pb, 0.01 to 1 $\mu\text{g}/\text{m}^3$ for Cd, and 0.001 to 0.09 $\mu\text{g}/\text{m}^3$ for Se. For the medium building fire, worst-case concentrations in air range from 0.001 to 2 $\mu\text{g}/\text{m}^3$ for Pb, 0.002 to 0.2 $\mu\text{g}/\text{m}^3$ for Cd, and 0.0002 to 0.02 $\mu\text{g}/\text{m}^3$ for Se. For the large building fire, worst-case concentrations in air range from 0.001 to 2 $\mu\text{g}/\text{m}^3$ for Pb, 0.003 to 0.3 $\mu\text{g}/\text{m}^3$ for Cd, and 0.0003 to 0.03 $\mu\text{g}/\text{m}^3$ for Se.

Worst-case concentrations in ambient air are comparable to about an order of magnitude for the small, medium, and large building fires; the highest results are associated with the small building fire. The similarity in the results, across building/fire sizes, indicates that the competing effects of mass emission rate (larger fires have higher mass emissions) and heat release rate (larger fires with higher heat flux have greater plume dispersion) are approximately counterbalanced.

Table 4. Summary of Exposure Point Concentrations in Air – Small Building Fire

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
Pb emissions from c-Si PV						
Mass Pb emission rate (ER; g/s)	6.25E-02	2.08E-02	1.04E-02	2.60E-03	1.30E-03	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	9.60E+01	9.60E+01	9.60E+01	9.60E+01	9.60E+01	Table 3

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12] [13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	1.37E+0 ₂	9.60E+01	9.60E+01	8.64E+0 ₁	6.72E+01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	9	2.0	1.0	0.23	0.09	Eq. 1
PAC-1 ($\mu\text{g}/\text{m}^3$)	150	150	150	150	150	[16]
PAC-2 ($\mu\text{g}/\text{m}^3$)	120,000	120,000	120,000	120,000	120,000	[16]
PAC-3 ($\mu\text{g}/\text{m}^3$)	700,000	700,000	700,000	700,000	700,000	[16]
Ratio of max. conc. to PAC-2	7.16E-05	1.67E-05	8.34E-06	1.88E-06	7.29E-07	
Cd emissions from CdTe PV						
Mass Cd emission rate (ER; g/s)	6.71E-03	2.24E-03	1.12E-03	2.80E-04	1.40E-04	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	9.60E+0 ₁	9.60E+01	9.60E+01	9.60E+0 ₁	9.60E+01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12] [13]
Maximum normalized concentration	1.37E+0 ₂	9.60E+01	9.60E+01	8.64E+0 ₁	6.72E+01	Eq. 2

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
(MNC; $\mu\text{g}/\text{m}^3$ per g/s)						
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	1	0.2	0.1	0.02	0.01	Eq. 1
AEGL-1 ($\mu\text{g}/\text{m}^3$)	130	130	100	63	41	[15]
AEGL-2 ($\mu\text{g}/\text{m}^3$)	1,400	960	760	400	200	[15]
AEGL-3 ($\mu\text{g}/\text{m}^3$)	8,500	5,900	4,700	1,900	930	[15]
Ratio of max. conc. to PAC-2	6.59E-04	2.24E-04	1.41E-04	6.04E-05	4.70E-05	
Se emissions from CIS PV						
Mass Se emission rate (ER; g/s)	6.67E-04	2.22E-04	1.11E-04	2.78E-05	1.39E-05	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	9.60E+01	9.60E+01	9.60E+01	9.60E+01	9.60E+01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12] [13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	1.37E+01	9.60E+01	9.60E+01	8.64E+01	6.72E+01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	0.09	0.02	0.01	0.002	0.001	Eq. 1

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
PAC-1 ($\mu\text{g}/\text{m}^3$)	600	600	600	600	600	[16]
PAC-2 ($\mu\text{g}/\text{m}^3$)	6,600	6,600	6,600	6,600	6,600	[16]
PAC-3 ($\mu\text{g}/\text{m}^3$)	40,000	40,000	40,000	40,000	40,000	[16]
Ratio of max. conc. to PAC-2	1.39E-05	3.23E-06	1.62E-06	3.64E-07	1.41E-07	

Table 5. Summary of Exposure Point Concentrations in Air – Medium Building Fire

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
Pb emissions from c-Si PV						
Mass Pb emission rate (ER; g/s)	1.56E+00	5.21E-01	2.60E-01	6.51E-02	3.26E-02	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	7.43E-01	7.43E-01	7.43E-01	7.43E-01	7.43E-01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[11][13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	1.06E+00	7.43E-01	7.43E-01	6.69E-01	5.20E-01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	2	0.4	0.2	0.04	0.02	Eq. 1

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
PAC-1 ($\mu\text{g}/\text{m}^3$)	150	150	150	150	150	[16]
PAC-2 ($\mu\text{g}/\text{m}^3$)	120,000	120,000	120,000	120,000	120,000	[16]
PAC-3 ($\mu\text{g}/\text{m}^3$)	700,000	700,000	700,000	700,000	700,000	[16]
Ratio of max. conc. to PAC-2	1.39E-05	3.23E-06	1.61E-06	3.63E-07	1.41E-07	
Cd emissions from CdTe PV						
Mass Cd emission rate (ER; g/s)	1.68E-01	5.59E-02	2.80E-02	6.99E-03	3.50E-03	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	7.43E-01	7.43E-01	7.43E-01	7.43E-01	7.43E-01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12][13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	1.06E+00	7.43E-01	7.43E-01	6.69E-01	5.20E-01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	0.2	0.04	0.02	0.005	0.002	Eq. 1
AEGL-1 ($\mu\text{g}/\text{m}^3$)	130	130	100	63	41	[15]
AEGL-2 ($\mu\text{g}/\text{m}^3$)	1,400	960	760	400	200	[15]
AEGL-3 ($\mu\text{g}/\text{m}^3$)	8,500	5,900	4,700	1,900	930	[15]

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
Ratio of max. conc. to PAC-2	1.28E-04	4.33E-05	2.74E-05	1.17E-05	9.10E-06	
Se emissions from CIS PV						
Mass Se emission rate (ER; g/s)	1.67E-02	5.56E-03	2.78E-03	6.94E-04	3.47E-04	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	7.43E-01	7.43E-01	7.43E-01	7.43E-01	7.43E-01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12][13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	1.06E+00	7.43E-01	7.43E-01	6.69E-01	5.20E-01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	0.02	0.004	0.002	0.0005	0.0002	Eq. 1
PAC-1 ($\mu\text{g}/\text{m}^3$)	600	600	600	600	600	[16]
PAC-2 ($\mu\text{g}/\text{m}^3$)	6,600	6,600	6,600	6,600	6,600	[16]
PAC-3 ($\mu\text{g}/\text{m}^3$)	40,000	40,000	40,000	40,000	40,000	[16]
Ratio of max. conc. to PAC-2	2.69E-06	6.26E-07	3.13E-07	7.04E-08	2.74E-08	

Table 6. Summary of Exposure Point Concentrations in Air – Large Building Fire

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
Pb emissions from c-Si PV						
Mass Pb emission rate (ER; g/s)	6.25E+00	2.08E+00	1.04E+00	2.60E-01	1.30E-01	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	2.73E-01	2.73E-01	2.73E-01	2.73E-01	2.73E-01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12] [13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	3.91E-01	2.73E-01	2.73E-01	2.46E-01	1.91E-01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	2	0.6	0.3	0.1	0.02	Eq. 1
PAC-1 ($\mu\text{g}/\text{m}^3$)	150	150	150	150	150	[16]
PAC-2 ($\mu\text{g}/\text{m}^3$)	120,000	120,000	120,000	120,000	120,000	[16]
PAC-3 ($\mu\text{g}/\text{m}^3$)	700,000	700,000	700,000	700,000	700,000	[16]
Ratio of max. conc. to PAC-2	2.04E-05	4.74E-06	2.37E-06	5.34E-07	2.08E-07	
Cd emissions from CdTe PV						

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
Mass Cd emission rate (ER; g/s)	6.71E-01	2.24E-01	1.12E-01	2.80E-02	1.40E-02	Eq. 3
Maximum 1-hr normalized concentration ($\mu\text{g}/\text{m}^3$ per g/s)	2.73E-01	2.73E-01	2.73E-01	2.73E-01	2.73E-01	Table 3
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12] [13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	3.91E-01	2.73E-01	2.73E-01	2.46E-01	1.91E-01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	0.3	0.06	0.03	0.007	0.003	Eq. 1
AEGL-1 ($\mu\text{g}/\text{m}^3$)	130	130	100	63	41	[15]
AEGL-2 ($\mu\text{g}/\text{m}^3$)	1,400	960	760	400	200	[15]
AEGL-3 ($\mu\text{g}/\text{m}^3$)	8,500	5,900	4,700	1,900	930	[15]
Ratio of max. conc. to PAC-2	1.88E-04	6.37E-05	4.02E-05	1.72E-05	1.34E-05	
Se emissions from CIS PV						
Mass Se emission rate (ER; g/s)	6.67E-02	2.22E-02	1.11E-02	2.78E-03	1.39E-03	Eq. 3
Maximum 1-hr normalized	2.73E-01	2.73E-01	2.73E-01	2.73E-01	2.73E-01	Table 3

	Averaging Time (min)					
Parameter	10	30	60	240	480	Note
concentration ($\mu\text{g}/\text{m}^3$ per g/s)						
Persistence Factor (unitless)	1.43	1	1	0.9	0.7	[12] [13]
Maximum normalized concentration (MNC; $\mu\text{g}/\text{m}^3$ per g/s)	3.91E-01	2.73E-01	2.73E-01	2.46E-01	1.91E-01	Eq. 2
Maximum concentration (MC; $\mu\text{g}/\text{m}^3$)	0.03	0.01	0.003	0.001	0.0003	Eq. 1
PAC-1 ($\mu\text{g}/\text{m}^3$)	600	600	600	600	600	[16]
PAC-2 ($\mu\text{g}/\text{m}^3$)	6,600	6,600	6,600	6,600	6,600	[16]
PAC-3 ($\mu\text{g}/\text{m}^3$)	40,000	40,000	40,000	40,000	40,000	[16]
Ratio of max. conc. to PAC-2	3.95E-06	9.20E-07	4.60E-07	1.04E-07	4.03E-08	

7. Risk Characterization

7.1 Acute Noncancer Hazards

The predicted worst-case concentrations in ambient air resulting from a fire are transient in nature; as discussed above, inhalation exposures are assumed to occur over a short duration of between 10 minutes and 8 hours. The time it takes for materials to be released from the modules during a fire can vary. As a worst-case, release over a range of acute time periods of interest is assumed. The potential acute noncancer health effects associated with these short-term (acute) inhalation exposures are evaluated through a comparison of predicted exposure point concentrations with AEGL and PAC criteria. PAC are based on AEGL, Emergency Response Planning Guidelines (ERPG) from the American Industrial Hygiene Association [25] or Temporary Emergency Exposure Limits (TEEL) criteria from USDOE [26], in

that order of preference (preference order established because of the more extensive review of animal and human studies for AEGL and ERPG than TEEL).

The AEGL and PAC criteria represent threshold exposure limits for the general public. Note that AEGL provide criteria specific to acute exposure periods ranging from 10 minutes to 8 hours, whereas PAC only provide criteria based on a 60-minute exposure period. Use of PAC criteria is conservative for averaging times less than 60 minutes but overestimates the tolerable effects threshold for averaging times exceeding 60 minutes. The resulting uncertainty is less than an order of magnitude as discussed in section 8.2. In contrast, the AEGL criteria are specific to each averaging time (Fig. 2).

Three levels are distinguished by varying degrees of severity of toxic effects, as follows, with each level defined in the same way for both AEGL and PAC

- AEGL-1 or PAC-1 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
- AEGL-2 or PAC-2 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3 or PAC-3 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects.

The AEGL-2 or PAC-2 criteria were used by the Bavarian Environmental Protection Agency to determine whether there is a serious (disabling) risk to potential receptors [6], and that approach is also followed in this report.

The comparison of predicted exposure point concentrations with the AEGL and PAC criteria is presented in Table 4 (small building fire), Table 5 (medium building fire), and Table 6 (large building fire). For all three types of building fire, predicted concentrations are below AEGL-2/PAC-2 thresholds (Figs. 1-3), and also below AEGL-1/PAC-1 and AEGL-3/PAC-3 thresholds, for all averaging times.

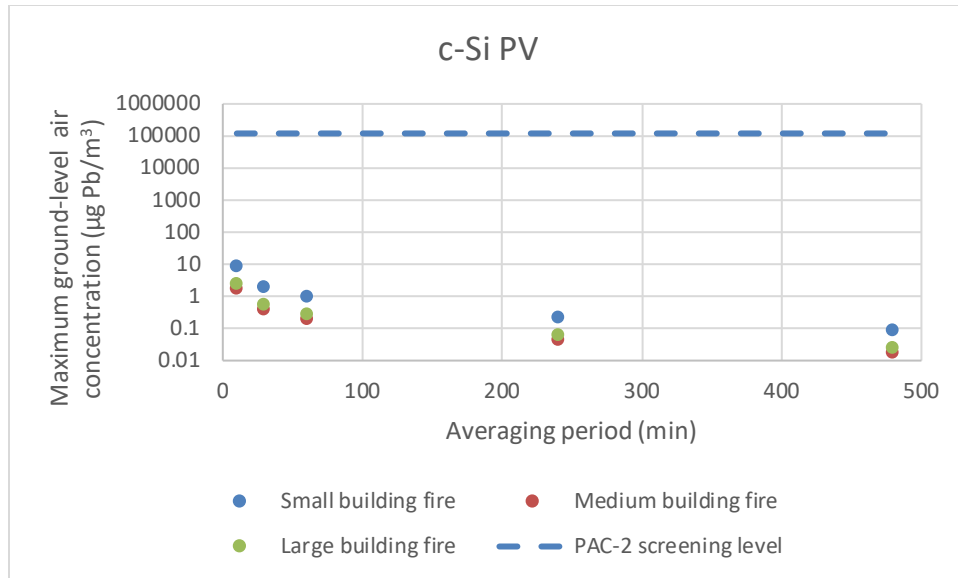


Figure 1: Maximum ground-level ambient air Pb concentration and PAC-2 acute exposure screening level [16] for small, medium, and large building fires with rooftop c-Si PV.

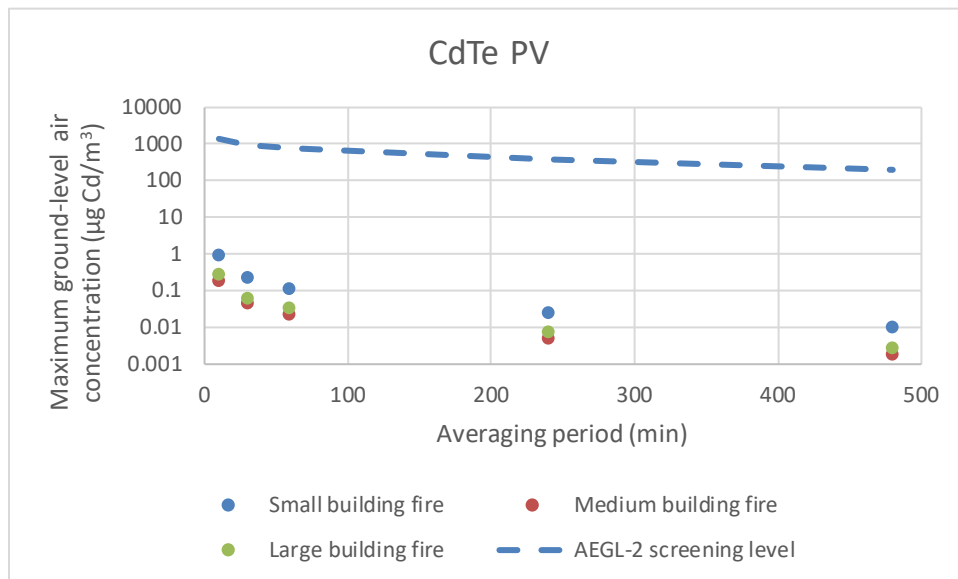


Figure 2: Maximum ground-level ambient air Cd concentration and AEGL-2 acute exposure screening level [15] for small, medium, and large building fires with rooftop CdTe PV.

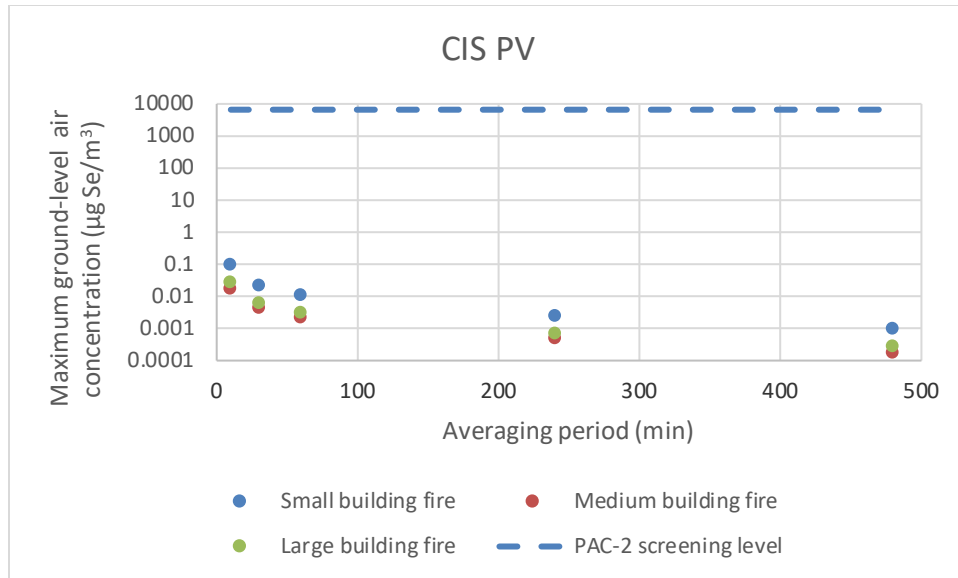


Figure 3: Maximum ground-level ambient air Se concentration and PAC-2 acute exposure screening level [16] for small, medium, and large building fires with rooftop CIS PV.

7.2 Incremental Cancer Risks

The potential for chemicals to cause cancer is typically based on assumed chronic (long-term) exposure. However, to be health protective and to understand whether the dose associated with a potential one-time short-term exposure associated with a fire could theoretically result in a significant probability that the receptors develop cancer over the course of their lifetime, this screening-level methodology estimates the incremental cancer risks associated with short-term inhalation exposure. The potential incremental cancer risk associated with inhalation is quantified in accordance with USEPA inhalation risk assessment methodology [14]:

$$\text{RISK} = \text{URF} \times \text{CA} \times \frac{\text{ED}}{\text{AT}_{\text{ca}}} \quad (\text{Eq. 4})$$

RISK = inhalation cancer risk, *i.e.*, the incremental probability of an individual developing cancer as a result of lifetime inhalation exposure to a particular chemical (unitless);

URF = inhalation unit risk factor, *i.e.*, the excess cancer risk associated with lifetime inhalation exposure to a unit concentration of 1 µg/m³ of a particular chemical (per µg/m³);

CA = exposure point concentration of chemical in air (µg/m³);

ED = exposure duration (hr); and

AT_{ca} = averaging time for carcinogenic effects (hr).

The inhalation carcinogenic potency is described by the inhalation unit risk factor (URF). The inhalation unit risk factor is defined as the upper-bound excess lifetime cancer risk estimated to result from

continuous (lifetime) exposure to a carcinogen present in air at a unit concentration of $1 \mu\text{g}/\text{m}^3$. The inhalation unit risk factors for Pb and Cd used in this health screening evaluation are the values of 1.20×10^{-5} and $1.80 \times 10^{-3} (\mu\text{g}/\text{m}^3)^{-1}$ published by OEHHA [27] and USEPA [28], respectively. An inhalation unit risk factor is not applicable for Se as selenium and its compounds are not classified as carcinogens, with the exception of selenium sulfide [28], and the latter is not present in CIS PV.

Potential incremental cancer risks for the small, medium, and large fire scenarios are calculated using the exposure point concentrations and exposure duration associated with the 10-minute exposure scenario (Tables 4-6), which produces the highest product of concentration and duration and thus the highest incremental cancer risk (per Eq. 4). In accordance with standard USEPA risk assessment methodology [29], carcinogenic health effects are evaluated by averaging the total cumulative exposure over a 70-year lifetime. Thus, the averaging time for carcinogenic effects (AT_c) is assumed to be 613,200 hours (*i.e.*, 70 years).

The potential incremental cancer risks associated with inhalation of Pb and Cd from PV modules in small, medium, and large building fires are documented in Table 7. These estimated potential incremental cancer risks are less than the 1×10^{-6} (one in a million) risk level that is typically considered to be a negligible risk level by regulatory agencies like USEPA [30].

Table 7. Potential Inhalation Cancer Risk

		Value				
Parameter		Small Building	Medium Building	Large Building	Units	Source/Note
Pb emissions from c-Si PV						
CA	Exposure point concentration in air (Pb)	9	2	2	$\mu\text{g}/\text{m}^3$	10-minute exposure; see Tables 4 through 6
URF	Inhalation unit risk factor	1.20E-05	1.20E-05	1.20E-05	per $\mu\text{g}/\text{m}^3$	[27]
ED	Exposure duration	0.17	0.17	0.17	hr	10-minute exposure
AT_{ca}	Averaging time for carcinogenic effects	613,200	613,200	613,200	hr	70 years [29]
RISK	Inhalation cancer risk	3E-11	5E-12	8E-12	–	Eq. 2
Cd emissions from CdTe PV						
CA	Exposure point concentration in air (Cd)	1	0.2	0.3	$\mu\text{g}/\text{m}^3$	10-minute exposure; see Tables 4 through 6
URF	Inhalation unit risk factor	1.80E-03	1.80E-03	1.80E-03	per $\mu\text{g}/\text{m}^3$	[28]

		Value				
Parameter		Small Building	Medium Building	Large Building	Units	Source/Note
ED	Exposure duration	0.17	0.17	0.17	hr	10-minute exposure
AT _{ca}	Averaging time for carcinogenic effects	613,200	613,200	613,200	hr	70 years [29]
RISK	Inhalation cancer risk	5E-10	9E-11	1E-10	–	Eq. 2
Pb emissions from CIS PV						
CA	Exposure point concentration in air (Pb)	0.09	0.02	0.03	µg/m ³	10-minute exposure; see Tables 4 through 6
URF	Inhalation unit risk factor	Not applicable	Not applicable	Not applicable	per µg/m ³	[28]
ED	Exposure duration	0.17	0.17	0.17	hr	10-minute exposure
AT _{ca}	Averaging time for carcinogenic effects	613,200	613,200	613,200	hr	70 years [29]
RISK	Inhalation cancer risk	Not applicable	Not applicable	Not applicable	–	Eq. 2

8 Uncertainties

8.1 Modeling Approach

The analysis presented above follows a screening-level approach, with the intent of developing order of magnitude-level estimates of potential risk after applying health-protective assumptions. Screening-level methods, such as used here, are meant to identify potential health risk scenarios that are greater than defined thresholds and may warrant further analysis. Concentrations in ambient air resulting from chemical release from modules during a fire are estimated using the USEPA-approved Gaussian plume dispersion model SCREEN3 [20]. Use of the SCREEN3 model for this purpose is consistent with USEPA guidance for an analogous scenario: chemical release from a burning pool of liquid or from a burning pile of tires modeled as a gaseous release from a flare point source. Modeling a fire as a point source is conservative, as this assumption neglects the initial dilution provided by air which is drawn-in over an area-wide fire source, such as PV on a roof [21]. Use of Gaussian plume dispersion modeling is consistent with the methodology of the Bavarian Environmental Protection Agency [6], which utilized

VDI guideline 3783, sheet 1 [7], a calculation method for estimating the Gaussian distribution of releases caused by accidents.

8.2 Other Topics

Other sources of uncertainty in the fire analysis include the following.

- Release efficiency. The experimental approach of Prume and Viehweg [3] is the basis for estimating chemical release rates of PV modules for the modeled fire scenarios. The estimated mass emission rates, and ultimately predicted concentrations of Pb, Cd, and Se in ambient air, are linearly proportional to this experimental release efficiency. Future experimental studies including commercial and emerging PV technologies (e.g., perovskite) and measuring emissions in both flue gas and fire water could confirm and supplement the chemical release rates used in this report. Emissions to air of Cd from CdTe PV and Se from CIGS PV in earlier PV fire tests [8][11] are comparable to those used here.
- Building size. As the building size and, therefore, the module array size increase, the mass of chemical released and, therefore, predicted normalized concentrations increase. The heat release rate and, therefore, plume dispersion also increase with building size, acting to decrease normalized concentrations. Building sizes of 100 m², 2,500 m², and 10,000 m² have been evaluated in this study, but in a real fire, the building size may differ from one of these assumptions. As shown in Figures 1-3, the competing factors of building size and heat release rate approximately counterbalance to within about an order of magnitude for the small, medium, and large building fires, with the highest results associated with the small building fire.
- Heat release rate. The assumed heat release rates from small, medium, and large building fires are based on an assumed heat flux of 50 kW/m², but in a real fire, the heat flux could be higher or lower (from about 25 to 150 kW/m² [24]). Higher heat release rates would result in greater plume rise and dispersion downwind from building fires; therefore, concentrations in ambient air and associated potential inhalation health impacts would likely be lower than estimated here. Conversely, lower heat release rates would result in lower plume rise and less downwind dispersion, though lower heat release rates also correspond to lower emission rates. In Prume and Viehweg [3], emissions from c-Si PV modules ranged from 61 mg Pb for the 25 kW burner to 600 mg Pb for the 150 kW burner with water spray; emissions from CdTe PV modules ranged from 19 mg Cd for the 25 kW burner to 29 mg Cd for the 150 kW burner with water spray, and emissions from CISPV modules ranged from 5.9 mg Se for the 25 kW burner to 4.8 mg Se for the 150 kW burner with water spray. The emissions from the 150 kW burner with water spray were used in this report due to the availability of data for emissions to both air and water.
- Building height. The dispersion modeling described above assumes a one-story building, as this will result in the greatest impact downwind. If a taller building were used, the plume would intersect the ground surface further from the source, resulting in lower predicted ground-level concentrations.
- Building shape. The dispersion modeling above assumes a square building. If other shapes were used, the distance from the center of the source to the edge of the building would vary depending on wind direction. The shorter the distance the greater the plume concentration. However, the shorter the distance, the less realistic the assumption that all the mass on the roof is available for emission into the plume, because the plume width is a function of the distance

downwind from the source of the plume to the receptor, in this case the edge of the building. Thus, as long as the plume width at the edge of the building is no wider than the side of the square building, a square-shaped building will always result in the worst-case estimate of plume concentration across all possible building shapes. The plume width at the edge of the building can be estimated by multiplying the lateral dispersion coefficient (σ_y) at the edge of the building by 4.3 [20]. For all modeling runs, the width of the plume is less than the length of building side – accordingly it is concluded that use of a square-shaped building results in a conservative estimate for all building shapes.

- **Averaging times.** Inhalation exposure assessment is based on averaging times ranging from 10 minutes to 8 hours. Whereas AEGLs provide screening criteria specific to each of these averaging times, PAC only provide criteria based on a 60-minute exposure period. For averaging times exceeding 60 minutes, the PAC criteria overestimate the tolerable effects threshold and for averaging times less than 60 minutes, the PAC criteria underestimate the tolerable effects threshold. Because the AEGL criteria vary by less than an order of magnitude over the averaging times (10 minutes to 8 hours), it is likely that the PAC criteria overestimate or underestimate tolerable effects thresholds by less than an order of magnitude for the same range of averaging times. Given that the maximum concentrations in Tables 4-6 are several orders of magnitude below PAC criteria, this source of uncertainty would not change the risk characterization.
- **Carcinogenicity.** The potential incremental cancer risk associated with inhalation of Pb and Cd is quantified in accordance with USEPA inhalation risk assessment methodology. The approach applied is conservative (assumptions are biased to being more health protective rather than less); it is uncertain whether short-term exposures as a result of a fire would increase an individual's lifetime probability of developing cancer, as cancer studies are based on long-term exposures.

8.3 Applicability

With regards to applicability of the risk assessment methods presented here to other chemicals and PV technologies, the methods can be applied given the availability of chemical release efficiency data, chemical fate and transport factors, and health screening values. For example, organic–inorganic halide perovskites are an emerging third generation PV technology that has achieved rapid advances in cell efficiency and considerable research and development funding and focus from academic and industrial research groups. The basic structure of a perovskite module consists of transparent conductive oxide (TCO-coated) glass, an electron transport layer, a perovskite absorber (e.g., $\text{CH}_3\text{NH}_3\text{PbI}_3$), a hole transport layer, and a back contact. Module packaging includes use of a standard encapsulant and a backsheets or back glass. A unique aspect of perovskite device manufacturing is relatively low processing temperature including the possibility of solution-based absorber deposition. These aspects increase the potential for relatively low electricity requirements in module manufacturing.

Perovskite PV modules are expected to contain small quantities of Pb content (~ 0.4 g per m^2 of module) [31] which is over an order of magnitude less than Pb content considered here for c-Si PV modules. Because perovskite PV technology is still in the process of being commercialized, data on release efficiency of Pb content in fire is not publicly available. Flue gas and fire water emissions testing similar to that conducted for c-Si, CdTe, and CIS PV modules [3] may be conducted for

commercial perovskite PV modules to enable application of the risk assessment methodologies presented here.

9. Evaluation of Potential Transport to Soil and Groundwater

In addition to potential direct impacts from short-term (acute) inhalation exposures, potential indirect impacts associated with transport to soil and/or groundwater has also been considered in this screening-level methodology. Extinguishing the fire with water may result in water-borne transport to soil and/or groundwater. In Appendix A, potential exposures in soil and groundwater have been quantified and compared to thresholds of concern, with a summary of results presented here.

The potential transport to soil and groundwater, and the subsequent potential exposures between human populations and substances in soil and groundwater, are evaluated in Appendix A. The key assumptions of these evaluations may be summarized as follows:

- Consistent with the inhalation-exposures scenario presented here in the main text, a small, medium, and large building fire are considered in the evaluation.
- The quantity of emissions to the water used to extinguish fire is estimated from measurements by Prume and Viehweg [3]. The resulting concentration in water in conjunction with the volume of annual precipitation that falls upon a site of the fire is assumed to be representative of the long-term average concentration in vadose (unsaturated) soil water throughout the site (Eq. A-1).
- Exposure point concentrations in soil and groundwater, resulting from transport from impacted vadose soil water, are estimated by USEPA soil screening guidance methodology (section A2).
- The potential significance of exposures to Pb, Cd, and Se is evaluated through comparison of exposure point concentrations to USEPA risk-based screening levels (RBSL) in soil and water and comparison to USEPA maximum contaminant levels (MCL) in water [30].

The results of this evaluation may be summarized as follows (Figures 4-9).

- For all three building scenarios considered in the evaluation, estimated exposure point concentrations of Pb, Cd, and Se in groundwater from c-Si, CdTe, and CIS PV are below the groundwater RBSL and MCL (Table A-2).
- For all three building scenarios considered in the evaluation, estimated exposure point concentrations of Pb, Cd, and Se in soil from c-Si, CdTe, and CIS PV are below the soil RBSL (Table A-2).

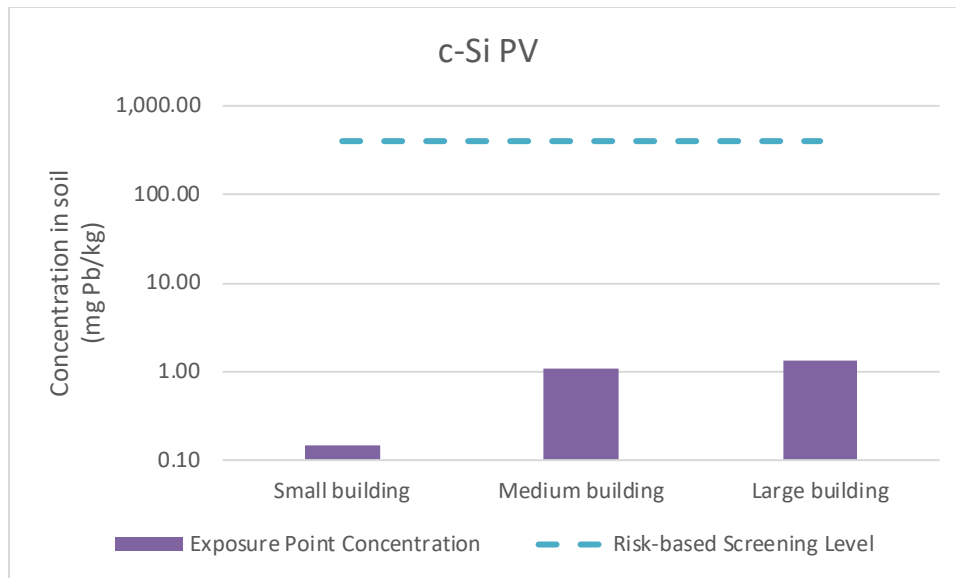


Figure 4: Exposure point concentration in soil in comparison to a USEPA risk-based soil screening level [30] for rooftop c-Si PV emissions of Pb to fire water for small, medium, and large building fires.

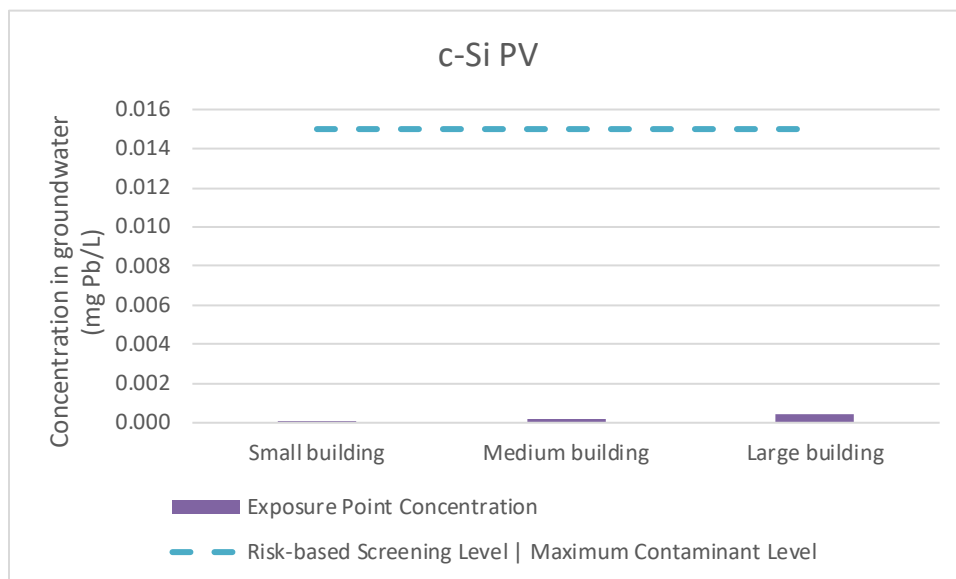


Figure 5: Exposure point concentration in groundwater in comparison to a USEPA risk-based groundwater screening level and maximum contaminant level [30] for rooftop c-Si PV emissions of Pb to fire water for small, medium, and large building fires.

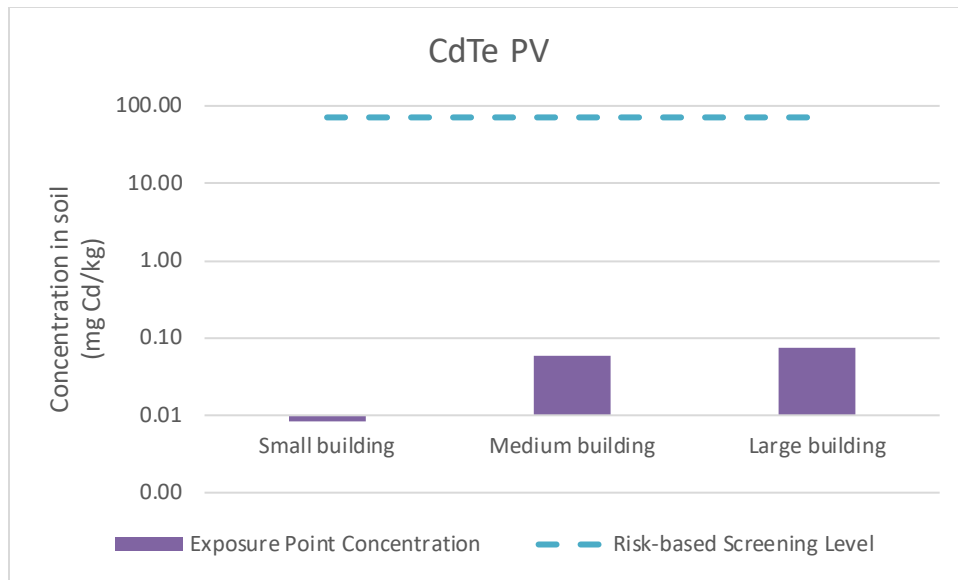


Figure 6: Exposure point concentration in soil in comparison to a USEPA risk-based soil screening level [30] for rooftop CdTe PV emissions of Cd to fire water for small, medium, and large building fires.

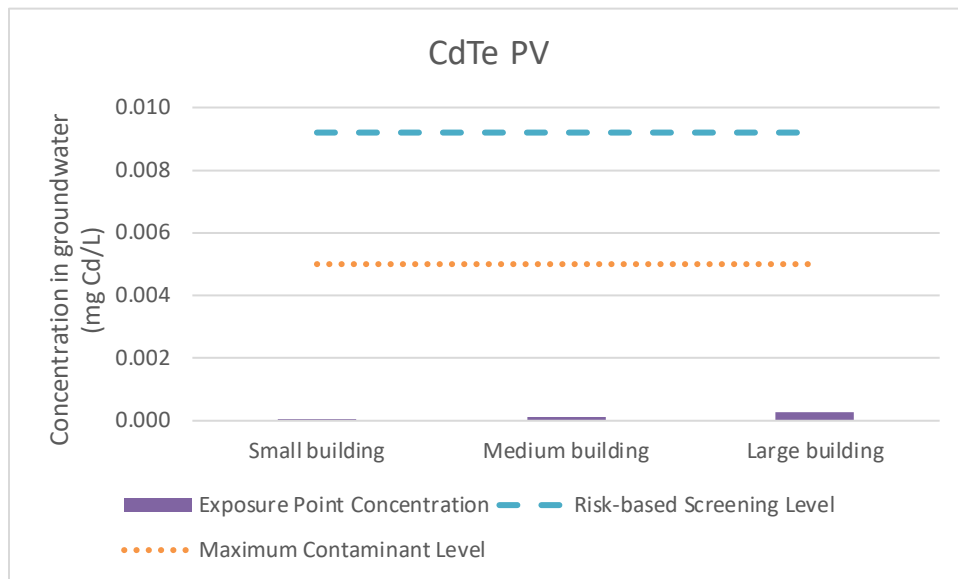


Figure 7: Exposure point concentration in groundwater in comparison to a USEPA risk-based groundwater screening level and maximum contaminant level [30] for rooftop CdTe PV emissions of Cd to fire water for small, medium, and large building fires.

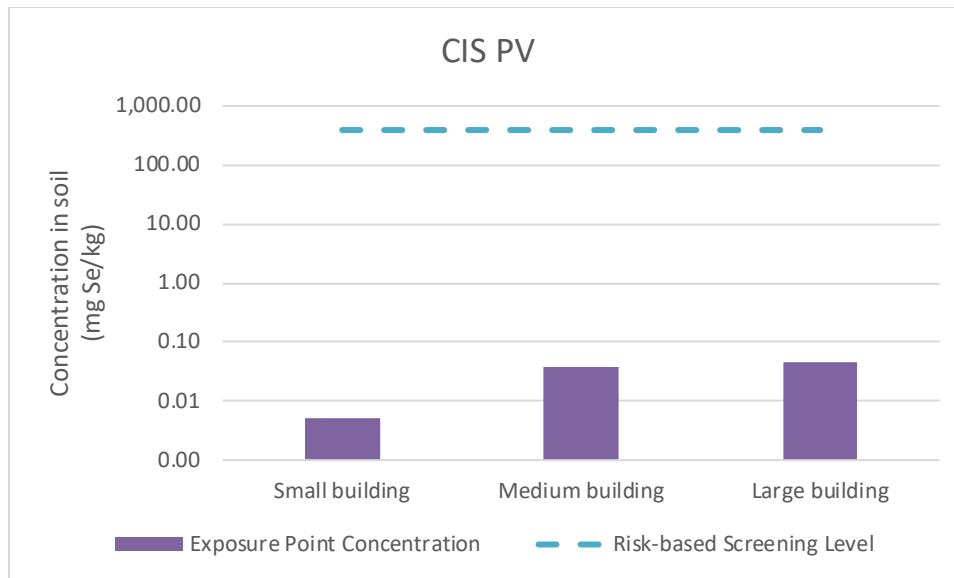


Figure 8: Exposure point concentration in soil in comparison to a USEPA risk-based soil screening level [30] for rooftop CIS PV emissions of Se to fire water for small, medium, and large building fires.

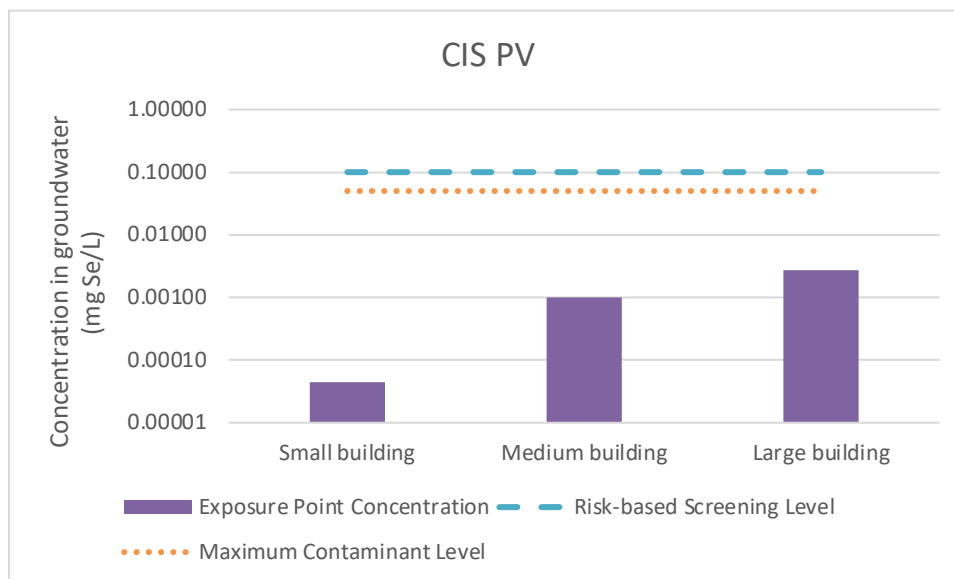


Figure 9: Exposure point concentration in groundwater in comparison to a USEPA risk-based groundwater screening level and maximum contaminant level [30] for rooftop CIS PV emissions of Se to fire water for small, medium, and large building fires.

10. Summary

This report presents methods for analysis of potential health impacts associated with emissions from burning photovoltaic modules during a building fire, as demonstrated through analysis for the highest prioritized chemical in each of three PV technologies: Pb content in c-Si PV, Cd content in thin film CdTe PV, and Se content in thin film CIS PV. The analysis quantifies potential impacts over a wide range of possible conditions, including building/fire size, receptor location, exposure duration and meteorological conditions, using a USEPA recommended Gaussian plume modeling approach. The analysis follows a conservative, screening-level approach, with the intent of developing order of magnitude-level estimates of potential risk after applying health-protective assumptions. Screening-level methods such as used here are meant to identify potential health risk scenarios that are greater than defined thresholds and may warrant further analysis.

The potential acute, noncancer health effects associated with inhalation are evaluated through a comparison of predicted exposure point concentrations with Acute Exposure Guidelines (AEGs) published by USEPA, and if not available for a particular chemical, Protective Action Criteria (PAC) published by USDOE. For the small, medium, and large building fires considered in the analysis, predicted Pb, Cd, and Se concentrations are below AEG/PAC for all three averaging times and screening thresholds investigated (AEG-1/PAC-1 for non-disabling health effects; AEG-2/PAC-2 for disabling; and AEG-3/PAC-3 for life-threatening). The potential incremental cancer risks associated with inhalation of Pb and Cd released from modules in small, medium, and large building fires are less than the 1×10^{-6} (one in a million) risk level that is typically considered to be a negligible risk level by regulatory agencies. (Note that incremental cancer risks associated with inhalation of Se potentially released from photovoltaic modules are not evaluated because Se is not classified as a carcinogen.) An evaluation (presented in Appendix A) of potential transport to soil or groundwater by transport by fire water, indicates potential impacts to soil and groundwater below risk-based screening limits and maximum contaminant levels.

Screening-level human health risk assessment has been conducted for potential ground-level receptors (neighborhood and general public), but not for potential occupational exposures to firefighters, which may be evaluated separately using occupational health screening values and accounting for occupational exposure factors. Potential ecological risks have also not been evaluated in this report. For a more complete evaluation of the potential health risks from PV modules on the roof of a building on fire, the methods demonstrated here for Pb, Cd, and Se can be applied to other chemicals of potential concern that are present in current or emerging PV technologies.

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APPENDIX A – EVALUATION OF POTENTIAL IMPACTS TO SOIL AND GROUNDWATER

A1. Introduction

This technical appendix documents an evaluation of potential chemical release from PV modules during a fire and subsequent transport to soil and groundwater. Chemicals released from a fire may be transported to soil and subsequently to groundwater via two primary pathways. First, and the primary focus of this appendix, is the result of the application of water to extinguish the fire. As a chemical is released from the modules during the fire, it may become entrained in the extinguishing water, and this water may run onto the ground surface. Second, as a chemical is released from the modules during the fire, it may become entrained in air lofting upward, and later deposited to the ground surface via airborne deposition. In this evaluation, it is explained why potential exposures associated with extinguishing water and subsequent soil deposition provide a conservative estimate of potential exposures associated with airborne deposition.

The approach followed in this evaluation may be summarized as follows.

- The potential mass of chemical released from modules during a building fire is estimated based on the amount of chemical present in the modules and the release efficiency in fire water from modules in a building fire.
- All of the chemical that is released from modules during the fire is assumed to be entrained in the water used to extinguish the fire. It is assumed that this chemical-impacted extinguishing water is discharged to the ground surface across the site.
- A long-term (annual) average concentration in onsite soil water in the vadose (unsaturated) soil column is estimated from the mass released from the modules, the assumed volume of water used to extinguish the fire, and the assumed volume of rainfall that falls on the site in 1 year.
- Given an estimated concentration in vadose soil water, the concentration in onsite vadose soil is estimated by assuming equilibrium partitioning between soil water and soil. This equilibrium soil concentration is used as the exposure point concentration in soil, for evaluating potential soil-based exposures.
- Given the same estimated concentration in vadose soil pore water, the potential concentration in the groundwater aquifer at the point of extraction for use as tap water is estimated in accordance with the dilution-attenuation factor (DAF) approach recommended by USEPA. This estimated groundwater concentration is used as the exposure point concentration in water, for evaluating potential water-based exposures.
- Potential health impacts associated with exposures in soil and groundwater are quantified by comparison of the estimated exposure point concentrations to risk-based screening levels and maximum contaminant levels.

This evaluation process is applied to three module-usage scenarios, consistent with the inhalation risk evaluation presented in the main text; *i.e.*, a small, medium, and large building. These methods are demonstrated in this report using example cases of evaluating potential human health risks from three

PV technologies: Pb content in c-Si PV, Cd content in thin film CdTe PV, and Se content in thin film CIS PV.

A2. Estimation of Exposure Point Concentrations in Soil and Groundwater

The potential transport of a chemical, released from modules during a fire, to soil and groundwater is evaluated in this section. Analogous to the smoke-inhalation exposure scenario evaluated in the main text, a small, medium, and large building are considered. Emissions from modules are estimated on the basis of the total mass of chemical contained in the modules and release-efficiency in fire water reported by Prume and Viehweg [1]. For c-Si PV, emissions of Pb to fire water ranged from 1.5 to 2.6 mg per module, corresponding to an average release efficiency in fire water of 0.016%, based on 13 g of Pb content per module (Table A-1). For CdTe PV, emissions of Cd to fire water ranged from 0.14 to 1.1 mg per module, corresponding to an average release efficiency in fire water of 0.010%, based on 6 g of Cd content per module (Table A-1). For CIS PV, emissions of Se to fire water ranged from 4.8 to 14 mg per module, corresponding to an average release efficiency in fire water of 0.17%, based on 5 g of Se content per module (Table A-1).

A2.1 Concentration in Soil

A screening-level annual average concentration in soil is estimated using a three-step process. First, the initial annual average concentration in vadose zone soil pore water is estimated from the mass of chemical released from the modules during the fire, the assumed volume of water used to extinguish the fire, and the assumed volume of rainfall that falls on the site in 1 year. Second, the concentration in onsite vadose soil is estimated by assuming equilibrium partitioning between soil pore water and soil. Third, a qualitative discussion is provided, explaining why potential exposures associated with extinguishing water and subsequent soil deposition is a conservative estimate of potential exposures associated with airborne dry deposition, and thus represent the maximum soil concentration likely to occur as a result of a fire.

A2.1.1 Concentration in Vadose Soil Water

Efforts to control a fire through the application of water may result in a chemical becoming entrained in the extinguishing water, which may flow off the building onto the surrounding ground surface. This water may then flow into the soil and mix with vadose zone pore water and with rainfall that infiltrates into the soil over time. To evaluate chronic exposures associated with transport to soil and groundwater, an annual average concentration in the soil pore water is required. A conservative estimate of annual average pore water concentration can be made by assuming that all of the chemical mass released from the modules is retained in the vadose zone water phase with no losses to partitioning into soil, and that this mass mixes with incoming rainwater without dilution from the initial soil pore water. With these assumptions, a screening level annual-average concentration in soil pore water can be estimated using the following equations:

$$C_W = \frac{F}{V_F + V_P} \quad (\text{Eq. A-1})$$

where:

- C_w = annual-average concentration in vadose soil pore water (mg/L);
- F = mass of chemical in fire water (mg);
- V_F = volume of water used to extinguish fire (L); and
- V_P = volume of annual precipitation that falls upon site (L).

$$F = M \times N \times RE \quad (\text{Eq. A-2})$$

where:

- M = mass of chemical content per module (g/module);
- N = number of modules on rooftop; and
- RE = release efficiency in fire water.

The volume of runoff water from a fire is uncertain. Field testing conducted on a “fruit shop” and a “sports store” reported volumes of water used to extinguish the fires of 3,600 and 2,000 liters, respectively [2]. Some of the water used to extinguish a fire will evaporate instead of becoming runoff water. The small building is similar to the “fruit shop” and “sports store” fires. For this evaluation, it is assumed that extinguishing the fire produces 1,000 liters of runoff water in the small building scenario. The medium and large buildings are assumed to produce proportionally more runoff water based on the difference in building roof area. The uncertainty in the volume of runoff water from a fire is unlikely to affect this evaluation because the annual rainwater volume is significantly greater than the extinguishing water volume. The annual rainwater volume is based on the average precipitation rate of the 97 climate stations included in the USEPA groundwater transport model used in this evaluation [3].

A2.1.2 Concentration in Impacted Soil

A worst-case concentration in onsite soil (Eq. A-3) is calculated under an assumption of equilibrium partitioning between soil water (with concentration given by Eq. A-1) and the solid soil phase. The equilibrium concentration represents the theoretical maximum concentration possible in the solid phase, given the concentration in soil pore water. The equilibrium soil concentration is estimated in accordance with the USEPA soil screening guidance [4]; it is noted that the equilibrium partitioning equation from the guidance is simplified here to account for Pb, Cd, and Se not being present in the air phase because they are nonvolatile.

$$CS = C_w \times \left(K_d + \frac{\theta_w}{\rho_{sg}} \right) \quad (\text{Eq. A-3})$$

where:

- CS = equilibrium concentration in soil (mg/kg);
- K_d = soil/soil-water partitioning coefficient (L/kg);

θ_w = soil water-filled porosity (unitless); and
 ρ_{sg} = soil particle density (kg/L).

This approach is conservative because it does not account for the loss of mass from the pore water, but instead assumes that the pore water constitutes an infinite source of chemical available for partitioning to the solid soil phase. In actuality, there is only a finite mass available (*i.e.*, the mass that is released from modules during the fire), and as some of this mass partitions into the solid soil phase, the concentration in the pore water would decrease. The equilibrium soil concentration predicted here, however, is based on the initial, higher pore water concentration; the actual equilibrium soil concentration would be lower.

The estimated screening level concentrations in soil for the three building sizes evaluated are presented in Table A-1.

A2.1.3 Qualitative Evaluation of Airborne Deposition

As noted above, a chemical released from the modules during the fire may become entrained in air lofting upward, and may later deposit to the ground surface via airborne deposition. Estimated exposures associated with extinguishing water provide a conservative estimate of potential exposures associated with airborne deposition, because the chemical released to the air will be dispersed over a much larger area than the area covered by water used to extinguish the fire. This increased dispersion will result in a significantly reduced mass per area of soil, as compared to the entrained-in-water transport scenario.

A2.2 Concentration in Impacted Groundwater

The USEPA soil screening guidance provides a method of estimating concentrations in groundwater based on concentration in vadose soil water [5]. The guidance estimates the dilution attenuation factor (DAF) between the chemical concentration in vadose soil water and the concentration in groundwater at the point of use (*i.e.*, at the location of a groundwater extraction well), which is assumed in the USEPA methodology to be located at the edge of the source.

$$C_{gw} = \frac{C_w}{DAF} \quad (\text{Eq. A-4})$$

where:

C_{gw} = concentration in groundwater aquifer at point of use (mg/L); and
DAF = dilution attenuation factor (unitless).

The DAF is dependent on the source area, which corresponds to the area of the site. Cal/EPA guidance recommends a building size of 10 meters by 10 meters and a site area of 1,000 square meters (m²) for residential evaluations [6]. There is no analogous site-area recommendation for commercial buildings. For the medium and large building scenarios, the area of the site not occupied by the building is assumed equal to the area of the site not occupied by the building under the small building scenario, *i.e.*, 900 m². Thus the site area is assumed to be 3,400 m² and 10,900 m² for the medium and large building scenarios, respectively. Source area-specific DAF values for the small, medium, and large

building scenarios are derived through linear interpolation of adjacent 95th percentile DAF values presented in the USEPA soil screening guidance technical background document [5]. These interpolated DAF values are used in the calculation of Pb, Cd, and Se concentrations in soil and groundwater in Table A-1.

Tab. A-1 Calculation of Concentrations in Soil and Groundwater

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
c-Si PV					
Mass of Pb content per module	13	13	13	g/module	Main text; Table 1
Number of modules on rooftop	63	1,563	6,250	module	
Release efficiency in fire water	0.016%	0.016%	0.016%	–	Based on [1]; see text
<i>Average Pb Concentration in Vadose Zone Soil Water</i>					
Mass of Pb in fire water	0.13	3.2	12.8	g	Eq. A-2
Volume of fire water	1,000	25,000	100,000	L	Adapted from [2]
Lot area	1,000	3,400	10,900	m ²	[6]; see text
Rainfall rate	31 (79)	31 (79)	31 (79)	in/yr (cm/yr)	[3]
Annual rainfall volume	791,852	2,692,295	8,631,182	L/yr	Based on area of site
Total annual infiltration volume	792,852	2,717,295	8,731,182	L	Sum of fire water volume and annual rainfall volume

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
Avg. conc. in vadose zone soil water	1.62E-04	1.18E-03	1.47E-03	mg/L	1-year average concentration (Eq. 1)
<i>Pb Concentration in Vadose Zone Soil</i>					
Soil water-filled porosity	0.3	0.3	0.3	unitless	[7]
Soil particle density	1.5	1.5	1.5	kg/L	[7]
Soil/soil-water partitioning coefficient	900	900	900	L/kg	[8]
Equilibrium concentration in soil	0.15	1.06	1.32	mg/kg	Eq. A-3
<i>Pb Concentration in Groundwater</i>					
DAF (1)	22.0	7.0	3.3	unitless	[5]
Concentration in groundwater	7.3E-06	1.7E-04	4.4E-04	mg/L	Eq. A-4
CdTe PV					
Mass of Cd content per module	6	6	6	g/module	Main text; Table 1
Number of modules on rooftop	139	3,472	13,889	module	
Release efficiency in fire water	0.010%	0.010%	0.010%	–	Based on [1]; see text
<i>Average Cd Concentration in Vadose Zone Soil Water</i>					
Mass of Cd in fire water	0.09	2.2	8.6	g	Eq. A-2
Volume of fire water	1,000	25,000	100,000	L	Adapted from [2]
Lot area	1,000	3,400	10,900	m ²	[6] ; see text

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
Rainfall rate	31 (79)	31 (79)	31 (79)	in/yr (cm/yr)	[3]
Annual rainfall volume	791,852	2,692,295	8,631,182	L/yr	Based on area of site
Total annual infiltration volume	792,852	2,717,295	8,731,182	L	Sum of fire water volume and annual rainfall volume
Avg. conc. in vadose zone soil water	1.09E-04	7.92E-04	9.86E-04	mg/L	1-year average concentration (Eq. A-1)
<i>Cd Concentration in Vadose Zone Soil</i>					
Soil water-filled porosity	0.3	0.3	0.3	unitless	[7]
Soil particle density	1.5	1.5	1.5	kg/L	[7]
Soil/soil-water partitioning coefficient	75	75	75	L/kg	[7]; default soil pH of 6.8
Equilibrium concentration in soil	0.01	0.06	0.07	mg/kg	Eq. A-3
<i>Cd Concentration in Groundwater</i>					
DAF (1)	22.0	7.0	3.3	unitless	[5]
Concentration in groundwater	4.9E-06	1.1E-04	3.0E-04	mg/L	Eq. A-4
CIS PV					
Mass of Se content per module	5	5	5	g/module	Main text; Table 1
Number of modules on rooftop	83	2,083	8,333	module	

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
Release efficiency in fire water	0.17%	0.17%	0.17%	–	Based on [1]; see text
<i>Average Se Concentration in Vadose Zone Soil Water</i>					
Mass of Se in fire water	0.8	20	78	g	Eq. A-2
Volume of fire water	1,000	25,000	100,000	L	Adapted from [2]
Lot area	1,000	3,400	10,900	m ²	[6] ; see text
Rainfall rate	31 (79)	31 (79)	31 (79)	in/yr (cm/yr)	[3]
Annual rainfall volume	791,852	2,692,295	8,631,182	L/yr	Based on area of site
Total annual infiltration volume	792,852	2,717,295	8,731,182	L	Sum of fire water volume and annual rainfall volume
Avg. conc. in vadose zone soil water	9.88E-04	7.21E-03	8.97E-03	mg/L	1-year average concentration (Eq. A-1)
<i>Se Concentration in Vadose Zone Soil</i>					
Soil water-filled porosity	0.3	0.3	0.3	unitless	[7]
Soil particle density	1.5	1.5	1.5	kg/L	[7]
Soil/soil-water partitioning coefficient	5	5	5	L/kg	[7]; default soil pH of 6.8
Equilibrium concentration in soil	0.01	0.04	0.05	mg/kg	Eq. A-3
<i>Se Concentration in Groundwater</i>					

Parameter	Small Building	Medium Building	Large Building	Units	Source/Note
DAF (1)	22.0	7.0	3.3	unitless	[5]
Concentration in groundwater	4.49E-05	1.03E-03	2.69E-03	mg/L	Eq. A-4

(1) A DAF value for the specific site area is calculate through linear interpolation of the 95th percentile DAF values for the closest lower and the closest higher areas presented in Table A1 of Appendix E of the USEPA soil screening guidance technical background document [5].

A3. Comparison of Exposure Point Concentrations to Risk-based Screening Levels

Exposure point concentrations in soil and groundwater calculated in Table A-1 are summarized in Table A-2 for the three exposure scenarios evaluated here, *i.e.*, a small, medium, and large building fire. Exposure point concentrations in soil are compared to the soil risk-based screening levels [8]. Exposure point concentrations in groundwater are compared to groundwater risk-based screening levels [8] and maximum contaminant levels (MCLs), which are legal standards that apply to public water systems. The U.S. federal MCLs for Pb, Cd, and Se are 0.015, 0.005, and 0.05 mg/L, respectively [8]. Exposure point concentrations of Pb, Cd, and Se in soil and groundwater are below the associated risk-based and regulatory screening levels for c-Si PV, CdTe PV, and CIS PV.

Potential exposures from soil and groundwater impacts are not summed because for each the soil evaluation and the groundwater evaluation, it is assumed that all of the mass released from the modules is transported to the media of concern. Therefore, adding these pathways together would “double count” the mass of chemical released from the modules.

Tab. A-2 Comparison of Exposure Point Concentrations to Risk-based Screening Levels and Maximum Contaminant Levels [8]

	Soil Evaluation		Groundwater Evaluation		
Building Size	Exposure Point Concentration	Risk-based Screening Level	Exposure Point Concentration	Risk-based Screening Level	Maximum Contaminant Level
	(mg/kg)	(mg/kg)	(mg/L)	(mg/L)	(mg/L)
c-Si PV (Pb)					
Small building	0.15	400	0.0000073	0.015	0.015

	Soil Evaluation		Groundwater Evaluation		
Building Size	Exposure Point Concentration	Risk-based Screening Level	Exposure Point Concentration	Risk-based Screening Level	Maximum Contaminant Level
	(mg/kg)	(mg/kg)	(mg/L)	(mg/L)	(mg/L)
Medium building	1.06	400	0.00017	0.015	0.015
Large building	1.32	400	0.00044	0.015	0.015
CdTe PV (Cd)					
Small building	0.01	71	0.0000049	0.0092	0.005
Medium building	0.06	71	0.00011	0.0092	0.005
Large building	0.07	71	0.00030	0.0092	0.005
CIS PV (Se)					
Small building	0.01	390	0.00004	0.100	0.050
Medium building	0.04	390	0.0019	0.100	0.050
Large building	0.05	390	0.003	0.100	0.050

A4. Uncertainties

A4.1 Concentration in Vadose Soil Water

The exposure periods for evaluation of potential non-cancer and cancer effects are one year and either 25 or 30 years, respectively. The release to the ground surface, however, is a one-time event. A one-year average concentration in vadose soil water is estimated from the chemical mass released from modules in fire water, the volume of extinguishing water runoff, and the annual volume of rainfall. The methodologies used to estimate soil and groundwater impacts both assume an infinite source in vadose soil water at this estimated concentration, whereas there is only a finite mass available. Long-term exposure point concentrations in soil and groundwater are likely to be lower than estimated here under the assumption of a continuous source in vadose soil water.

One-year concentrations in impacted media are calculated to compare to both cancer and non-cancer risk-based screening levels. This is conservative for comparison to cancer-based screening levels, which have a 25 or 30 year exposure duration. If rainfall over 25 or 30 years was included in the calculation of

the concentration in vadose soil water, the estimated concentration in water would be approximately a factor of 25 or 30 lower. The exposure point concentrations in soil and groundwater would be reduced by these same factors.

A4.2 Source Area for Transport to Soil and Groundwater

A key variable in estimating the exposure point concentrations in soil and groundwater is the area of impact. In this evaluation, it is assumed that infiltration of chemical-impacted extinguishing water results in impacted vadose soil water over the entire site area. For the small building scenario, both the assumed building size and assumed lot size are based on Cal/EPA guidance [6]; the site area is approximately 10 times greater than the building area. In the absence of any site-area guidance for larger buildings, the area of the site not occupied by the building is assumed equal to the area of the site not occupied by the building under the small building scenario. Thus, the area of these sites is uncertain but likely conservative.

As the site area increases, the annual volume of rainwater incident upon the site increases, and (for constant building size, *i.e.*, mass of chemical in the system) the estimated concentration in the vadose soil water decreases. The predicted equilibrium concentration in soil decreases linearly with the concentration in soil pore water (see Eq. A-3). Thus, the assumption of a larger site area (for constant building size) would result in lower estimated soil impacts.

With respect to potential groundwater impacts, the assumed site area affects the calculation in two different ways, which act in opposing directions. As noted above, as site area increases, the estimated concentration in pore water decreases; thus the strength of the potential source of groundwater impacts decreases. As site area increases, however, the dilution-attenuation factor (DAF) also decreases, as the larger source would have a greater impact on groundwater concentrations (at constant pore water concentration [5]). These competing factors tend to cancel out (Eq. A-4), such that predicted groundwater concentrations are relatively insensitive to the assumed area over which a chemical is released as a result of a fire. An additional factor potentially affecting groundwater impacts is whether downspouts concentrate water runoff from buildings. For commercial buildings, downspout runoff could connect directly to sanitary sewer and not impact the ground, but since the condition of downspouts may be compromised during fire, the downspout scenario is not considered in this methodology.

Further, the extent to which the groundwater aquifer may become impacted is limited by the finite mass released from the modules in a fire. It is conservatively assumed, however, that there is an infinite source available, such that the entire site-wide vadose zone, from the ground surface to the groundwater table, is impacted at the predicted equilibrium partitioning concentration. Therefore, actual impacts to groundwater may be lower than estimated here.

A5. Summary

This appendix documents the methodology and results of an evaluation of potential exposures to chemicals that could be present in soil and groundwater as a result of release from modules during a fire. Consistent with the inhalation risk evaluation presented in the main text, three module-usage scenarios have been considered in the evaluation: a small, medium, and large building. The major steps

of this evaluation were to: 1) model the transport of emissions to soil and groundwater and estimate exposure point concentrations in these media; 2) compare the estimated exposure point concentrations to risk-based screening levels and maximum contaminant levels to evaluate the potential significance of the exposures. These methods are demonstrated using example cases of evaluating potential human health risks from three PV technologies: Pb content in c-Si PV, Cd content in thin film CdTe PV, and Se content in thin film CIS PV.

Two pathways by which chemicals released from modules in a fire could potentially be transported to soil and groundwater have been considered in this evaluation. The primary pathway, which is evaluated in detail in this appendix, is the result of the application of water to extinguish the fire. It is assumed that, as a chemical is released from the modules during the fire, it may become entrained in the extinguishing water, and this water may run onto the ground surface. Alternatively, as a chemical is released from the modules during the fire, it may become entrained in air lofting upward, and later deposit to the ground surface via airborne dry deposition. This latter pathway (airborne dry deposition) has been discussed qualitatively, as the potential impacts to soil and groundwater would be less than those associated with the former pathway (water-borne transport), which have been quantified here. In the cases considered, estimated exposure point concentrations of Pb, Cd, and Se in soil and groundwater are below risk-based screening limits and maximum contaminant levels for c-Si, CdTe, and CIS PV, respectively.

A6. References

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