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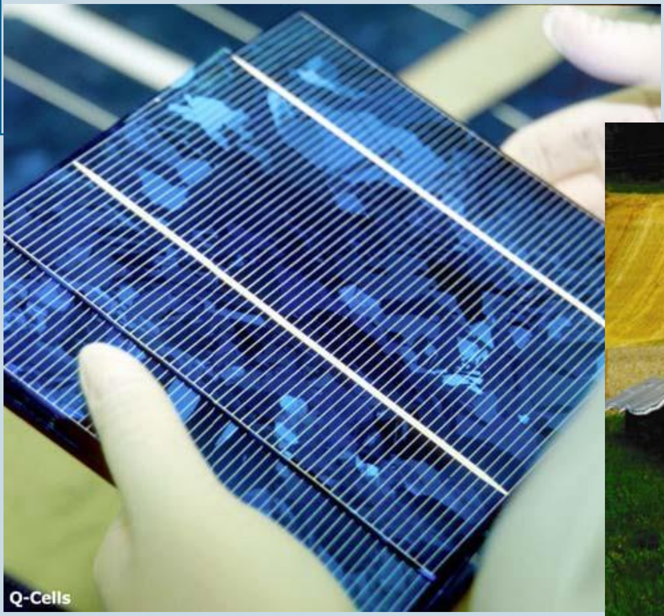
Human Health Risk Assessment Methods for PV
Part 2: Breakage Risks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Karlstadt Laudenbach, Germany (810 kW); Phoenix Solar

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

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INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS TECHNOLOGY COLLABORATION PROGRAMME

Human health risk assessment methods for PV Part 2: Breakage Risks

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List of Units

cm - centimeter

$g/m^2/s$ – grams per square meter per second

kg/mg –kilograms per milligrams

kg/L – kilograms per liter

L/kg – liters per kilogram

m – meter

m/s – meters per second

m^2 – square meters

mg/L – milligrams per liter

mg/kg – milligrams per kilogram

$\mu g/m^3$ – micrograms per cubic meter

Executive Summary

Photovoltaic (PV) modules are designed and tested for long-term durability in harsh outdoor environments, but a small percentage may break during installation or operation. Some industry stakeholders have expressed concerns regarding potential human exposure to hazardous materials should a PV module break in the field. To evaluate these concerns, screening-level risk assessment methods are presented that can estimate emissions that may occur when broken PV modules are exposed to rainwater, estimate the associated chemical concentrations in soil, groundwater and air, and finally compare these exposure-point concentrations to health-protective screening levels based on 1×10^{-6} cancer risk and hazard quotient of 1. The screening-level methods can be used to decide whether further evaluation of potential health risks is warranted. A few example scenarios demonstrate application of the methods.

Specifically, this report presents an analysis of potential human health impacts associated with rainwater leaching from broken modules for two PV technologies, focusing on release of the highest-prioritized chemical element for each: lead (Pb) content in crystalline-silicon (c-Si) PV modules and cadmium (Cd) content in thin film cadmium telluride (CdTe) PV modules. The prioritization of these chemical elements for analysis is based on stakeholder interest. Because the methodology is chemical-specific, the risk assessment results for these chemicals cannot be directly generalized to other chemicals, although the risk assessment methodology can be applied to other chemicals.

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, consistent with general risk assessment approaches recommended by the U.S. National Academy of Sciences (NAS), U.S. Environmental Protection Agency (USEPA), and International Electrotechnical Commission (IEC). In particular, this report quantifies what are expected to be the worst-case potential health impacts over a range of possible conditions, including breakage rate, concentration in leachate, soil/soil-water partitioning coefficient, and dilution-attenuation factor, utilizing a fate and transport modeling approach that is typically used in regulatory contexts. The evaluation of Pb content in c-Si PV modules is based on current usage of Pb in metallization pastes and solders, which could be higher than future usage if Pb-free pastes and solders achieve greater market penetration. The evaluation of Cd content in CdTe PV modules is based on current usage of CdTe in the semiconductor layer, which could be higher than future usage if semiconductor layer thickness is reduced.

The specific exposure scenarios which are considered in this screening evaluation include:
- a residential building with an array of modules on the rooftop;
- a commercial office building with an array of modules on the rooftop;
- a large-scale ground-mounted installation of modules (“utility-scale solar”).

The primary mechanism by which chemicals are assumed to be released is by leaching by rainwater that falls on broken modules, with breakage defined as modules with cracked glass or broken module pieces. Under this potential release scenario, chemicals could be transported in rainwater runoff from the modules to the soil and soil pore water, which further could be transported to groundwater. In addition, once in the soil, impacted soil particles could be emitted to air by wind erosion. These chemical release and transport mechanisms are applied on an annual basis to the above three scenarios: residential building, commercial office building, and utility-scale solar. Exposure scenarios related to the release scenarios are thus ingestion of and dermal contact with impacted soil; ingestion, inhalation, and dermal contact with impacted groundwater as tap water; and inhalation of impacted soil particles as airborne dust.

Exposure point concentrations of chemicals in various exposure media are estimated through fate and transport modeling conducted in accordance with USEPA modeling guidance and site-specific assumptions. Worst-case impacts from transport to soil and transport to groundwater are mutually exclusive, based on conservation of mass considerations; there is only a finite (limited) chemical mass available, based on the number of broken modules at the site. In this evaluation, potential transport to soil and to groundwater are therefore quantified separately.

Exposure point concentrations (Pb and Cd from c-Si and CdTe PV, respectively) are estimated as follows.

- Under the residential building scenario, exposure point concentrations are quantified for onsite residents who are potentially exposed to chemicals in soil, air, and groundwater.
- Under the commercial office building and utility-scale solar scenarios, exposure point concentrations are quantified for onsite commercial/industrial workers who are exposed to chemicals in soil and air during a normal 40-hour workweek, and offsite residents who are exposed to chemicals in groundwater and air.

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, including the following:

Modeling parameter	Assumption
Breakage	Module breakage remains undetected in the field over exposure duration (1 yr)
Source area	Entire building rooftop is covered with modules
Leachate concentration	All rainwater impacting the module is assumed to contact the broken module area with USEPA Method 1312 Synthetic Precipitation Leaching Procedure used to estimate leachate concentration
Soil-water partitioning	Equilibrium partitioning representing the theoretical maximum concentration possible in the solid phase, for a given concentration in soil pore water, assuming that pore water constitutes an infinite source of chemical available for partitioning to the solid soil phase
	Dry soil conditions prior to the runoff, or no mixing with existing soil moisture
Soil-air partitioning	Dust present in ambient air is comprised entirely of impacted site soil that has been entrained in ambient air
	Dust emissions and dispersion from multiple small impacted soil areas are modeled as a single larger impacted soil area
Transport to groundwater	A groundwater extraction well is located 25 feet away from all impacted soil areas
	Chemicals released from every broken module are transported to the same groundwater extraction well

In addition to single point estimates of exposure point concentrations, distributions and contributions to variance are estimated with Monte Carlo uncertainty simulation by varying breakage rate, concentration in leachate, soil/soil-water partitioning coefficient, and dilution-attenuation factor. In all exposure scenarios of the Monte Carlo simulation, the breakage rate contributes to about half of the variance due to the large range considered (annual breakage rate from 0 to 100%).

Potential health effects are evaluated through a comparison of predicted exposure point concentrations in soil, air, and water with risk-based screening levels published by USEPA, which account for chronic exposure to chemicals, protective of both cancer and non-cancer endpoints. Exposure point concentrations of Pb and Cd for c-Si and CdTe PV module breakage, respectively, in residential, commercial, and utility-scale systems are several orders of magnitude below USEPA health screening values in soil, air, and groundwater for both the single point estimates (Tables 12-13, Figures 3-4) and Monte Carlo uncertainty simulation (Figures 6-8). USEPA screening levels are utilized because of their specificity to exposure scenarios (residential and commercial/industrial). Health screening levels can differ by region, but exposure point concentrations of Pb and Cd for c-Si and CdTe PV module breakage, respectively, are also within air and water quality guidelines from the World Health Organization.

In this report, only two chemicals (Pb and Cd) have been used to demonstrate the human health risk assessment methodology for field breakage of two PV module technologies (c-Si and CdTe). Other environmentally sensitive elements (e.g., In, Ag, Cu, Se, Sn, Ni) are used in commercial PV modules and new PV technologies (e.g., perovskite) are emerging. Thus the results presented here do not represent a complete human health risk assessment for PV module breakage, although the results are suggestive of low risk for the prioritized chemicals examined. The screening-level methods employed in this report can be used in future work 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. Potential ecological risks have 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 technology collaboration programmes 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.

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 (DOE) and is now operated jointly by the National Renewable Energy Laboratory and SolarPower Europe. Support from DOE and SolarPower 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 break in the field. This report is part 2 of a three-part series on human health risk assessment methods for PV. Part 1 addressed potential health risks resulting from modules exposed to fire and Part 3 will address potential health risks resulting from module disposal.

1 Introduction

Broken modules refer to PV modules with cracked glass or broken module pieces which may result from extreme weather or human factors. Annual field breakage rates estimated based on warranty return data are low (~0.04%), and due to use of laminated glass in PV modules, field breakages mainly consist of stress and impact fractures in which modules remain intact albeit with a number of cracks in the protective outer glass [1]. Some industry stakeholders have expressed concerns regarding potential human exposure to hazardous materials should a PV module break in the field. To evaluate these concerns, risk assessment methods are presented that can estimate emissions that may occur when broken PV modules are exposed to rainwater, estimate the associated chemical concentrations in soil, groundwater, and air, and finally compare these exposure-point concentrations to health-protective screening levels.

PV modules are constructed as solid-state monolithic devices to achieve long-term field durability to withstand harsh environmental conditions for 25 years or more. Encapsulation of the module components is achieved with use of a polymer laminate material (e.g., ethylene vinyl acetate or polyolefin) in a glass-encapsulant-backsheet or glass-encapsulant-glass design (Figure 1). While c-Si PV modules are primarily constructed with glass-backsheet design and thin film modules are constructed with glass-glass design, glass-glass c-Si PV modules are now also being deployed. The encapsulant bond strength is on the order of 5 megapascals (~50 kg/cm^2) making the modules very difficult to break open (i.e., to separate the front and back of the module). For example, this high encapsulant bond strength is the reason why efficient delamination is a core challenge for recyclers attempting to reverse engineer an end-of-life PV module into its raw materials [2].

The high encapsulant bond strength also limits the potential for rainwater leaching of cracked or broken PV modules by maintaining the module components inside the glass-glass or glass-backsheet structure in the case of breakage. For example, in a landfill experiment, PV modules were crushed with six passes by a landfill compactor with a contact load of 50 tons, and the crushed module pieces maintained the front-back encapsulation [3]. In the case of field breakage, exposure of module components to rainwater is therefore limited to the surface area of the crack or the perimeter of the broken module piece.

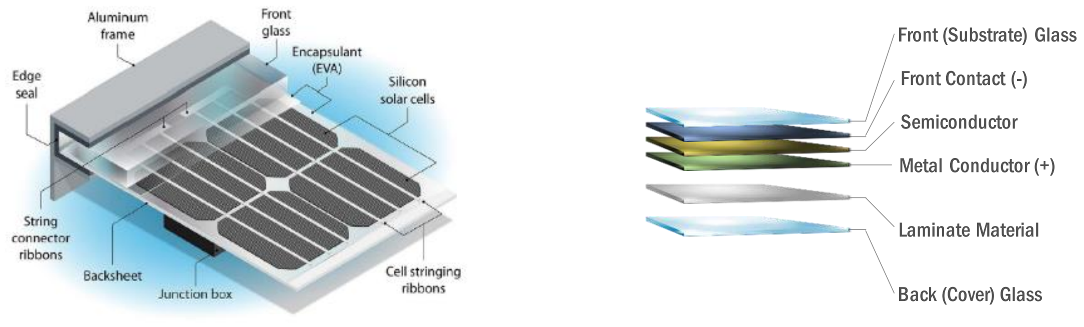


Figure 1. C-Si (left) [4] and thin film (right) [5] PV module components

PV module durability is essential for both product safety and long-term performance. Durability testing of commercial PV modules involves market entry product quality, reliability, and safety testing (e.g., UL 1703, IEC 61215, IEC 61730) as well as extended reliability testing (e.g., Thresher test, Long-term sequential test, Atlas 25+ certification) that repeat the market entry test procedures over multiple cycles and sequences. Additional tests evaluate specific degradation or failure mechanisms such as IEC 62804 potential induced degradation resistance, IEC 61701 salt mist corrosion, and IEC 60068 dust and sand resistance.

Test protocols are implemented in environmental chambers that accelerate product degradation due to weathering, for example, using temperature and humidity extremes as well as biasing modules with voltage and current. Damp heat testing exposes the module to extreme steady state humidity and temperature (85% relative humidity at 85˚C) to stress the adhesion of product interfaces. The humidity freeze test also attempts to weaken these interfaces with the presence of extreme heat and moisture and then freezing the moisture to form ice crystals to further damage the interface. Thermal cycling accelerates the potential stress induced by materials with differing thermal expansion coefficients by exposing them to extreme temperature swings between 85˚C and -40˚C. Light soaking accelerates light induced degradation by controlling irradiance and temperature. These and other reliability tests are summarized in Table 1 and illustrated in [6].

Table 1. Example PV module quality and reliability test equipment [7]

Reliability testing equipment	Purpose
Environmental Chambers	Acceleration of Package Degradation (Weathering)
Light Soak Units	Acceleration of Light Induced Degradation
Dynamic/Static Load	Simulate Wind, Snow and Ice Loads
Reverse current overload	Determine Risk of Fire Under Reverse Current Fault Condition
UV Chambers	Evaluate Materials and Adhesive Bonds Susceptible to UV Degradation
Hail Impact	Verify Module Capable of Withstanding the Impact of Hail
Hot Spot Test	Ability of the Module to Withstand Heating Effects from Soiling or Shading
Instron Material Tester	Material Property Testing, Connector Force
Tracker Actuator Test Rig	Acceleration of Tracker Actuator Cyclical Stress

With regard to evaluating human health risks from PV module breakage, a paradigm for human health risk assessment was first developed by the U.S. National Academy of Sciences [8] and consists of four main steps of:

1. hazard identification,
2. dose-response assessment,
3. exposure analysis, and
4. risk characterization.

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 [9], the highest-prioritized chemical element from two PV technologies are evaluated in this report as illustrative examples of the application of the methods developed herein (section 2.2). Dose-response assessment is incorporated in the use of health screening values (section 5). Exposure analysis includes the characterization of chemical emissions (section 3) and environmental fate of emissions (section 4). Risk characterization and associated uncertainties are covered in sections 5 and 6.

Screening-level human health risk assessment methods, based on the above paradigm but specific to PV, have been outlined by the International Electrotechnical Commission [9]. 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 two PV technologies: Pb content in c-Si PV and Cd content in thin film CdTe PV.

The evaluation of Pb content in c-Si PV modules and Cd content in CdTe PV modules are based on current usage as described above. Increased market penetration of Pb-free pastes and solders has been forecasted [10] which would reduce risks estimated in the c-Si PV case study. Future reduction in semiconductor layer thickness has been identified as part of a resource efficiency strategy for thin film PV [5], which would reduce risks estimated in the CdTe PV case study.

2 Conceptual Site Model

2.1 *Overview*

Figure 2 summarizes the screening level methodology for evaluating potential human health risks from PV module breakage. The exposure scenarios which are considered in this evaluation include:

- a residential building with an array of modules on the rooftop;
- a commercial office building with an array of modules on the rooftop;
- a large-scale ground-mounted installation of modules (“utility-scale solar”).

Potential exposure pathways and exposed populations depend on the exposure scenario, as described below in sections 2.3 and 2.4. The screening methodology for estimating potential leachate concentrations and chemical fate and transport from point of emissions to point of exposure are presented in sections 3 and 4. Exposure point concentrations are compared to risk-based screening levels in section 5 and uncertainties in key parameters are evaluated in section 6.

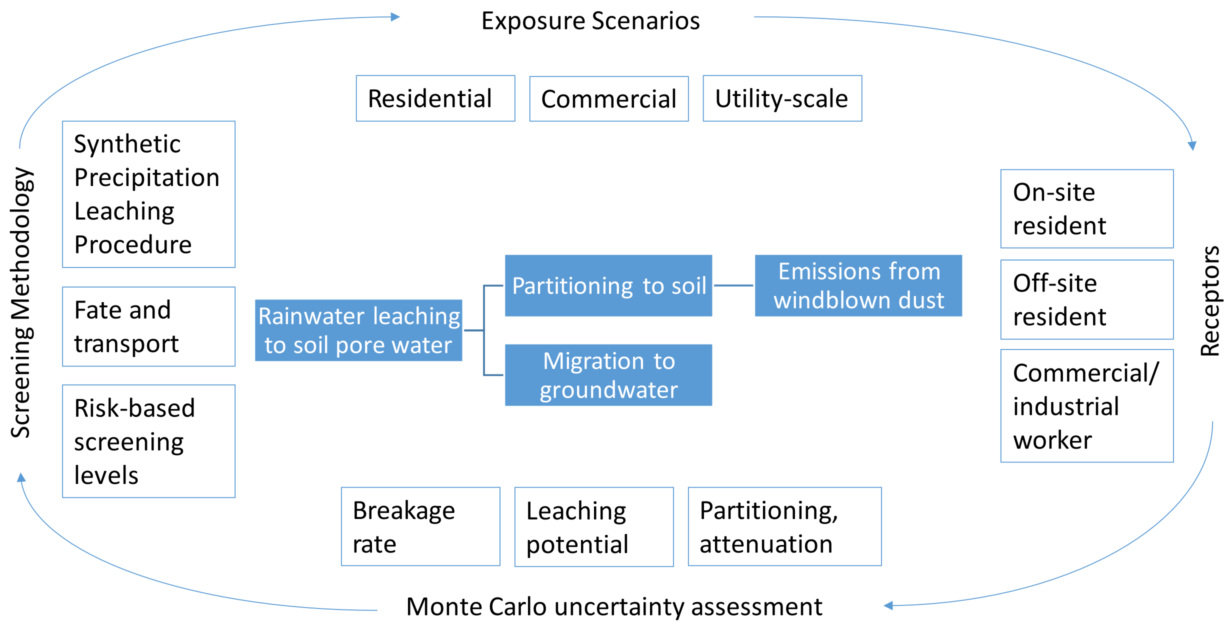


Figure 2. Conceptual site model for evaluating potential human health risks from PV module breakage

2.2 Chemicals Included in Evaluation

The chemicals which are included in this evaluation are Pb content in c-Si PV and Cd content in CdTe PV. In addition to these chemicals of potential concern, other metals found in commercial PV modules are Ag, Al, Cu, Ga, In, Ni, Se, Sn, Te, and Zn [4]. While the methods developed in this report are not applied to these latter metals, they could be evaluated in future research.

2.3 Potential Release Mechanisms and Transport Pathways

The hypothetical release mechanism considered in this evaluation is release from modules by leaching to rainwater that falls on broken modules while they are in use. For this release mechanism, it is assumed that chemicals are transported in rainwater runoff to soil and groundwater, and then from soil to air by dust emissions. It is assumed that an underlying groundwater aquifer is used as a source of residential tap water.

Potential transport to soil, air and groundwater are quantified separately, under worst-case assumptions for each specific transport pathway. Because it is not possible for each pathway to experience worst-case impacts simultaneously, the exposures from each pathway are not summed, but rather are evaluated against health screening levels separately.

2.4 Potentially Exposed Populations and their exposure routes

The human populations with potential to experience exposures to product-related chemicals, and that are considered in this quantitative evaluation, are described below by exposure scenario. Specific exposure factors are based on USEPA Risk Assessment Guidance for Superfund Part B [11] and USEPA Soil Screening Guidance [12][13] and are incorporated into USEPA Regional Screening Levels [14] described in Section 5. For example, on-site residents are expected to spend most, if not all, their time at home, whereas workers are only expected to be on-site during work hours.

Residential Building Scenario

Residents who live at a site where the modules are used ("on-site residents") are assumed to experience exposures to impacted soils through incidental ingestion and dermal contact and dust inhalation, and exposure to impacted groundwater used as residential tap water.

Commercial Office Building Scenario

Commercial workers who work at a site where modules are used ("onsite commercial/industrial workers") are assumed to experience exposures to impacted soils through incidental ingestion and dermal contact and dust inhalation. Commercial workers are assumed to have access to water from public water supplies, and so are not assumed to experience exposures to impacted groundwater. Offsite residents living near the site may potentially use the groundwater as a source of domestic tap water, and thus these offsite residents are assumed to experience exposures to impacted groundwater. It is assumed that offsite residents are not directly exposed to impacted site soils, but are exposed via inhalation of dust that has blown from the site to the offsite residential land use.

Utility-Scale Solar Scenario

The exposed populations and exposure routes for the utility-scale solar scenario are the same as for the commercial office building scenario. Workers at the utility-scale solar site ("onsite commercial/industrial workers") are assumed to experience exposures to impacted soils through incidental ingestion and dermal contact and dust inhalation. Workers are assumed to have access to water from public water supplies, and so are not assumed to experience exposures to impacted groundwater. Offsite residents are assumed to experience exposures to impacted groundwater used as residential tap water. Offsite residents are also assumed to experience inhalation exposures to dust that is transported downwind from the site.

3 Leachate concentrations

The determination of chemical leachate concentrations that may be released from the modules into rainwater is based on the results of laboratory testing. The USEPA Method 1312 Synthetic Precipitation Leaching Procedure (SPLP) [15] measures the mobility of analytes in simulated rainwater (Table 2). The average chemical concentrations measured in SPLP leachate, as summarized in Table 2, are used to represent chemical concentrations in rainfall runoff from broken PV modules.

The SPLP methodology allows for two pH values (pH 4.2 for U.S. locations east of the Mississippi River and pH 5.0 for U.S. locations west of the Mississippi River). The lower pH value is used here to represent acid rain and higher potential for leaching. The type, duration, intensity, and quantity of precipitation can vary by location and by precipitation event within a given location. By fully submerging PV module pieces in solution, the SPLP test provides greater exposure of module components to simulated rainwater than an actual rain event. In arid regions where PV capacity factors are also highest, lack of precipitation also limits the potential for rainwater leaching. The 20:1 liquid to solid ratio in the SPLP test corresponds to 1 L of rainwater per 50 grams of PV module pieces or 400 L of rainwater for a 20 kg PV module. Assuming PV module area of 2 m^2, 400 L of rainwater corresponds to 20 cm of rainfall over the surface area of the PV module. However, unlike a precipitation event where rainwater has potential one-time contact with a PV module component followed by runoff, the SPLP test has continuous contact of simulated rainwater with PV module components over the test duration (18 hours).

Table 2. Summary of Regulatory Leaching Test Methods and Results for c-Si and CdTe PV modules

Geography		United States [1]	United States [15-17]	Germany [1]	Japan [1]
Leaching Test		U.S. EPA Method 1311 (TCLP)	U.S. EPA Method 1312 (SPLP)	DIN EN 12457-4:01-03	MOE Notice 13/JIS K 0102:2013 (JLT-13)
Test type		Waste characterization	Rainwater leaching (used in this study)	Waste characterization	Waste characterization
Sample size (cm)		1	1	1	0.5
Sample preparation		Water-jet cutting	Water-jet cutting	Water-jet cutting	Hammering
Solvent		Sodium acetate/ acetic acid (pH 2.88 for alkaline waste; pH 4.93 for neutral to acidic waste)	H_2SO_4/HNO_3 (60/40 wt %); pH 4.2	Distilled water	Distilled water
Liquid:Solid Ratio		20:1	20:1	10:1	10:1
Treatment Method		End-over-end agitation (30±2 rotations per minute)	End-over-end agitation (30±2 rotations per minute)	End-over-end agitation (5 rotations per minute)	End-over-end agitation (200 rotations per minute)
Test Temperature		23±2˚C	23±2˚C	20˚C	20˚C
Test Duration		18±2 hr	18±2 hr	24 hr	6 hr
Leachate Pb Concentration (mg/L)	c-Si PV	3-11	0.069±0.056 (n=4)	-	Non-detect (<0.01) - 0.90
	CdTe PV	Non-detect (<0.1)	Non-detect (<0.020) (n=3)	-	Non-detect (<0.01)
Leachate Cd Concentration (mg/L)	c-Si PV	Non-detect (<0.1)	Non-detect (<0.010) (n=4)	-	Non-detect (<0.01)
	CdTe PV	0.22	0.017±0.002 (n=3)	0.0016 - 0.0040	0.10-0.13

SPLP samples were prepared using water-jet cutting, a cutting method similar to coring that provides precision and field representativeness in sample preparation [18]. Some previous non-standard leaching tests have utilized finely ground samples and/or extended extraction cycles, which can provide data on the total quantity of metals in a sample, but not their availability under realistic field breakage conditions [1]. As shown in Table 2, there are several regulatory leaching test methods which vary by geography, with most tests used for waste characterization for landfill disposal. The results from the SPLP test are used in this report because the objective of the test is to characterize rainwater leaching.

4 Fate and Transport

4.1 Overview

Fate and transport modeling refers to the mathematical representation of the movement of chemicals through a medium and from one medium to another. In the context of exposure assessment, fate and transport modeling is used to estimate concentrations of chemicals in an exposure medium, given concentrations of chemicals in an impacted medium.

The mechanism by which chemicals are assumed to be released from modules is by leaching by rainwater that falls on broken modules. This chemical release mechanism, and the subsequent chemical transport to soil, groundwater, and air, are considered on an annual basis for the land uses in this evaluation: residence, commercial office building, and utility-scale solar. Section 4 will introduce fate and transport methods with point estimates for parameters and then uncertainty will be quantified in section 6, including reporting of ranges or distributions of parameters.

Chemical Concentrations in Module Leachate and Vadose Zone Soil Pore Water

The extent to which metals could leach from broken modules to rainwater is based on the SPLP testing of the modules (Table 2). Based on manufacturer warranty data, this evaluation considers potential chemical release from broken modules, with an average annual breakage rate of 0.04% [1]. Given an assumed annual chemical release from modules to rainwater, the following specific potential transport pathways are quantitatively evaluated:

- transport to soil and vadose zone soil pore water by rainwater discharge;
- transport from soil to ambient air by dust emissions; and
- transport from vadose zone soil pore water to groundwater that is assumed to be a source of domestic tap water.

Rainwater that falls upon a rooftop installation of modules and is collected by a gutter system is thus a mixture of module leachate and unimpacted rainwater that falls upon intact modules or bare roof. The concentration of each chemical in the collected rainwater is a function of the concentration in module leachate, and the fraction of the rooftop that is covered with broken modules, as expressed by the module breakage rate (Eq. 1). This calculation is applicable to roof-mounted module installations (residential building and commercial office building scenarios).

$$CV = C \times B \qquad \text{(Eq. 1)}$$

where:

CV = concentration of chemical in vadose zone soil pore water (mg/L);
C = concentration (C) in SPLP leachate (mg/L);
B = annual breakage rate (%)

In the residential building and commercial office building scenarios, it is assumed that the comingled rooftop runoff is conveyed from the rooftop via one or more downspouts, and discharged onto the ground surface over an area of 1 m^2 per downspout. Chemical concentrations in vadose zone soil pore water at these discharge locations are assumed equal to the concentrations in the rooftop runoff discharge. This approach assumes dry soil conditions prior to the runoff, or no mixing with existing soil moisture. The vadose zone soil pore water throughout the rest of each site is assumed to be unimpacted.

The utility-scale solar scenario is different from the others, in that the module installation is ground-mounted. For this type of site, it is assumed that the rainwater is not collected or otherwise managed, but rather runs off each module onto the ground surface below over an area of ground surface equal to the module area. Chemical concentrations in vadose zone soil pore water at the locations of PV module breakage are represented by SPLP leachate concentrations. This approach assumes that all rainwater impacting the module is exposed to the broken part of the module. The vadose zone soil pore water throughout the rest of each site is assumed to be unimpacted.

Exposure Point Concentrations in Soil

Exposure point concentrations in soil are derived to evaluate an exposure scenario where potential receptors may be exposed to impacted soils through incidental ingestion and dermal contact (section 2.4). Given an estimated concentration of a chemical in vadose zone soil water, a worst-case concentration of the chemical in onsite soil is calculated under an assumption of equilibrium partitioning of the chemical between soil water and the solid soil phase. This approach assumes equilibrium is maintained on an annual basis using the SPLP leachate concentrations, whereas actual equilibrium between soil water and soil will depend on the frequency and magnitude of rain events. 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 [12][13]; it is noted that the equilibrium partitioning equation from the guidance is simplified here (Eq. 2) to account for the chemical not being present in the air phase because it is nonvolatile, *i.e.*, has a Henry’s Law constant of zero. Chemical-specific values for the soil/soil-water partitioning coefficient are recommended by USEPA [13][14] and are presented in Tables 3, 6, and 9. Default values for soil water-filled porosity (0.3) and soil dry bulk density (1.5 kg/L) from USEPA soil screening guidance [12] are used in all exposure scenarios.

$$CS_{eq} = CV \times \left(K_d + \frac{\theta_w}{\rho_b} \right) \qquad \text{(Eq. 2)}$$

where:

CS_{eq} = equilibrium concentration of chemical in soil (mg/kg);

CV = concentration of chemical in vadose zone soil pore water (mg/L);

K_d = soil/soil-water partitioning coefficient (L/kg);

θ_w = soil water-filled porosity (unitless); and

ρ_b = soil dry bulk density (kg/L).

The worst-case concentrations of chemical in soil calculated from Eq. 2 are assumed to exist over some fraction of the total site area, based on the manner in which the impacted water is discharged to the ground surface (a scenario-specific assumption; sections 4.2-4.4). Onsite human receptors are assumed to be exposed to site soils through incidental ingestion and dermal contact across the entire site. Therefore, exposure point concentrations of chemicals in soil are calculated as site-wide average concentrations that incorporate the areas of impacted and unimpacted soils.

$$\mathrm{CS} = \mathrm{CS}_{eq} \times \frac{\mathrm{IA}}{(\mathrm{SA - A})} \qquad \text{(Eq. 3)}$$

where CS is the exposure point concentration in soil (mg/kg); CS_{eq} is the equilibrium concentration in impacted soil (mg/kg); IA is the impacted area (m^2); SA is the site area (m^2); and A is the area of building (m^2).

Exposure Point Concentrations in Air

The two chemicals included in this evaluation (Pb and Cd) are non-volatile, and therefore would only be present in air in the particulate phase, not the gas phase. The concentration of a non-volatile chemical in air is the product of: 1) the concentration of dust in air; and 2) the concentration of the chemical in the airborne dust:

$$CA_{annual} = CD_{annual} \times CS_{eq} \times CF \qquad \text{(Eq. 4)}$$

where:

CA_{annual} = annual average concentration of chemical in air ($\mu g/m^3$);

CD_{annual} = annual average concentration of dust in air ($\mu g/m^3$);

CS_{eq} = concentration of chemical in impacted soil and dust (mg/kg);

CF = units conversion factor (10^{-6} kg/mg)

The concentration of each chemical in airborne dust is assumed to be the same as the concentration of the chemical in impacted soil, as it is assumed that the dust present in ambient air is comprised of only impacted site soil that has been entrained in ambient air. This is a worst case assumption since most of the site soil is not impacted.

For each of the three exposure scenarios considered in this evaluation, a worst-case concentration of dust in ambient air is estimated using the USEPA Gaussian plume dispersion model SCREEN3 [19], with a scenario-specific input assumption regarding the area of the emissions source (sections 4.2-4.4). 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), and evaluates the specific combination of wind speed and stability class that results in maximum 1-hour downwind concentration. The model allows the user to specify urban or rural land use in the vicinity of the emissions source. The urban option has been applied to the residential and commercial scenarios and the rural option has been applied to the utility-scale scenario. The optional automated distance array is employed for all model runs. Under this option, the SCREEN3 model places receptors at regular horizontal distances downwind from the emissions source, and also identifies the worst-case impact (i.e., highest predicted concentration) at any distance downwind from the source.

The assumed flux of soil into the air is the default value associated with wind erosion from the USEPA soil screening guidance (1.38×10^{-7} g/m^2/s) assuming mean annual surface wind speed of 4.69 m/s and no vegetative cover [13]. This flux is modeled over the scenario-specific source area by SCREEN3 to estimate the worst-case (highest at any onsite or offsite location) 1-hour dust concentration. The worst-case 1-hour concentration is converted to a worst-case annual-average concentration (Eq. 5) by applying a persistence factor of 0.08 developed by the USEPA that relates the concentration estimated using one averaging time to the concentration predicted using a different averaging time [20]. As this modeled dust concentration represents the worst-case impact at any onsite or offsite location, the exposure point concentrations of chemicals in air that are based on this modeled dust concentration (Eq. 4) may be conservatively used to characterize dust inhalation exposures to onsite or offsite receptors.

$$CD_{annual} = CD_{hourly} \times P \qquad \text{(Eq. 5)}$$

where:

CD_{annual} = annual average concentration of dust in air (µg/m^3);

CD_{hourly} = maximum 1-hour dust concentration in µg/m^3;

P = persistence factor 1-hour to annual-average conversion (unitless)

Exposure Point Concentrations in Groundwater

Given estimated concentrations of chemicals in vadose zone soil pore water, the potential concentrations of chemicals in the underlying groundwater aquifer at the point of extraction for use as domestic tap water are estimated in accordance with the dilution-attenuation factor (DAF) approach recommended in the USEPA soil screening guidance [12][13]. The concentrations estimated by this methodology are used as the exposure point concentrations of chemicals in groundwater.

The DAF is used to evaluate the migration of a chemical through soil to an underlying potable aquifer. Chemical migration through the unsaturated zone to the water table generally reduces the soil leachate concentration by attenuation processes such as adsorption and degradation, and groundwater transport in the saturated zone further reduces concentrations through attenuation and dilution. The reduction in concentration is represented by the DAF, defined as the ratio of original soil pore water concentration to the receptor point groundwater concentration. This approach assumes steady state flow, neglecting seasonal fluctuations in precipitation and groundwater flow [21].

The technical background document of the soil screening guidance provides a method of estimating concentrations in groundwater based on concentration in vadose zone soil pore water [21]. The guidance estimates the DAF between the chemical concentration in vadose zone soil pore water and the concentration in groundwater at the point of use (*i.e.*, at the location of a groundwater extraction well), which is assumed (by USEPA) to be located at the edge of the source.

$$\mathrm{CW} = \frac{\mathrm{CV}}{\mathrm{DAF}} \quad \text{(Eq. 6)}$$

where:

CW = exposure point concentration of chemical in groundwater (mg/L);

CV = concentration of chemical in vadose zone soil pore water (mg/L); and

DAF = dilution attenuation factor (unitless).

The DAF is dependent on the area of impacted vadose zone soil pore water, which is scenario-specific (sections 4.2-4.4).

4.2 Residential Building Scenario

The estimation of exposure point concentrations of chemicals in soil, air, and groundwater for the residential building scenario are calculated in accordance with the methodology described in Section 4.1, with scenario-specific input assumptions as noted below.

Chemical Concentrations in Module Leachate and Vadose Zone Soil Pore Water

The chemical concentration in module leachate is based on SPLP testing and is documented in Table 2.

In the residential building scenario, the building rooftop is assumed to be 10 meters by 10 meters (100 m^2), based on Cal/EPA vapor intrusion guidance for residential building evaluations [22]. It is further assumed that the entire building rooftop is covered with modules. This is an overestimate – as typically only about one-quarter of the total rooftop area of small buildings is suitable for solar PV [23] – and thus the risk is likely overestimated and health protective. Chemical concentrations in the comingled rooftop runoff are calculated based on the concentrations of chemicals in module leachate and the relative areas of the rooftop covered with intact and broken modules, as expressed by the breakage rate (Eq. 1).

In the residential building scenario, it is assumed that the comingled rooftop runoff is conveyed from the rooftop via a single downspout, and discharged onto the ground surface over an area of 1 m^2. Chemical concentrations in vadose zone soil pore water at this location are assumed equal to the concentrations in the rooftop runoff discharge. The vadose zone soil pore water throughout the rest of the site is assumed to be unimpacted. Chemical concentrations in impacted vadose zone soil pore water are documented in Table 3.

Exposure Point Concentrations in Soil

Worst-case concentrations of chemicals in onsite soil are calculated under an assumption of equilibrium partitioning between impacted vadose zone soil pore water and the solid soil phase per Eq. 2. There are no scenario-specific input assumptions to this calculation. Assumed soil properties are USEPA default values [13][14]. Equilibrium soil concentrations are presented in Table 3.

Onsite residents are assumed to be exposed to site soils through incidental ingestion and dermal contact across the entire site. Exposure point concentrations of chemicals in soil are therefore calculated as site-wide average concentrations, incorporating areas of impacted soils (at the worst-case concentrations predicted by equilibrium partitioning) and unimpacted soils. The site area is assumed to be 1,000 m^2, based on Cal/EPA vapor intrusion guidance for residential evaluations [22]. The calculation of exposure point concentrations of chemicals in onsite soil is documented in Table 3.

Table 3. Chemical concentrations in module leachate, chemical concentrations in vadose zone soil pore water, and equilibrium soil concentrations for residential building scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Concentration (C) in SPLP leachate in mg/L	0.069	0.017	Table 2
Annual breakage rate (B)	0.04%	0.04%	[1]
Annual concentration in vadose zone soil pore water (CV) in mg/L	0.0000276	0.0000068	Eq. 1
Soil water-filled porosity (θ_w) (unitless)	0.3	0.3	Default; [13]
Soil dry bulk density (ρ_b) in kg/L	1.5	1.5	Default; [13]
Soil/soil water partitioning coefficient (K_d) in L/kg	900	75	[13][14]
Equilibrium concentration in impacted soil (CS_{eq}) in mg/kg	0.025	0.00051	Eq. 2
Impacted area (IA) in m^2	1	1	Assumption based on single 1-m^2 downspout
Site area (SA) in m^2	1000	1000	[22]
Building area (A) in m^2	100	100	[22]

	Pb in c-Si PV	Cd in CdTe PV	Notes
Exposure point concentration in soil (CS) in mg/kg	2.8×10^{-5}	5.7×10^{-7}	Eq. 3

Exposure Point Concentrations in Air

In the residential building scenario, emissions of impacted dust are assumed to occur from the 1-m^2 area of impacted soil where the downspout discharges. Exposure point concentrations of chemicals in onsite and offsite ambient air (Table 4) are estimated from the modeled worst-case annual-average dust concentration and the exposure point concentrations of chemicals in soil, per Eq. 4. The worst-case annual-average dust concentration is estimated using the SCREEN3 model input parameters in Table 4 and the exposure point concentrations of chemicals in soil derived in Table 3.

Table 4. Exposure point concentrations in air in residential building scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Equilibrium concentration in impacted soil (CS_{eq}) in mg/kg	0.025	0.00051	Table 3
Dust Flux (g/m^2/s)	0.000000138	0.000000138	[13]
Source type	Area	Area	Ground source
Modeled area source size (m^2)	1	1	Assumption based on single 1-m^2 downspout
Source height (m)	0	0	Ground source
Human receptor height (m)	1.5	1.5	Assumption based on approximate breathing zone height
Urban/Rural option	Urban	Urban	Residential scenario
Choice of meteorology	Full	Full	Default
Terrain	Simple (Flat)	Simple (Flat)	Required for area source modeling [19]
Automated distance array?	Yes	Yes	Assumption

	Pb in c-Si PV	Cd in CdTe PV	Notes
Minimum downwind distance (m)	1	1	Assumption
Maximum downwind distance (m)	10000	10000	Assumption
Maximum 1-hour dust concentration (CD_{hourly}) in µg/m^3	0.01019	0.01019	Modeled result of SCREEN3 [19] based on above parameters
Persistence factor (P) 1-hour to annual-average conversion (unitless)	0.08	0.08	[20]
Annual average concentration of dust in air (CD_{annual}) in µg/m^3	0.000815	0.000815	Eq. 5
Concentration of chemical in air (CA_{annual}) in µg/m^3	2.0×10^{-11}	4.2×10^{-13}	Eq. 4

Exposure Point Concentrations in Groundwater

In the residential building scenario, as discussed above, impacted rainfall runoff from the building rooftop is discharged to the ground surface via a downspout. For the purpose of specifying the area of impacted vadose zone soil water which comprises the potential source of groundwater impacts (and for the purpose of determining the appropriate DAF for use in Eq. 6), the source area is the downspout discharge area of 1 m^2. Based on this source area, a 90th percentile DAF is obtained from the USEPA soil screening guidance technical background document [21]. The calculation of exposure point concentrations in groundwater per Eq. 6 is documented in Table 5.

Table 5. Exposure point concentrations in groundwater for residential building scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Annual concentration in vadose zone soil pore water (CV) in mg/L	0.0000276	0.0000068	Table 3
DAF (unitless)	37600	37600	[21]

	Pb in c-Si PV	Cd in CdTe PV	Notes
Exposure point concentration in groundwater (CW) in mg/L	7.3×10^{-10}	1.8×10^{-10}	Eq. 6

4.3 Commercial Office Building Scenario

The estimation of exposure point concentrations of chemicals in soil, air, and groundwater for the commercial office building scenario are calculated in accordance with the methodology described in Section 4.1, with scenario-specific input assumptions as noted below.

Chemical Concentrations in Module Leachate and Vadose Zone Soil Pore Water

Chemical concentrations in module leachate are the same for all exposure scenarios (see Table 2).

In the commercial office building scenario, the building rooftop is assumed to be 50 m by 50 m (2500 m^2). It is further assumed that the entire building rooftop is covered with modules. Chemical concentrations in the comingled rooftop runoff are calculated based on the concentrations of chemicals in module leachate and the relative areas of the rooftop covered with intact and broken modules, as expressed by the module breakage rate (Eq. 1).

In the commercial office building scenario, it is assumed that the comingled rooftop runoff is conveyed from the rooftop via downspouts, and discharged onto the ground surface over an area of 1 m^2 per downspout. As the assumed rooftop area of the commercial office building is 25 times greater than the assumed rooftop area of the residential building, it is also assumed the commercial office building has 25 times more downspouts than the residential building. Therefore, it is assumed the commercial office building has 25 downspouts. Chemical concentrations in vadose zone soil pore water at these 25 locations, each with area of 1 m^2, are assumed equal to the concentrations in the rooftop runoff discharge. The vadose zone soil pore water throughout the rest of the site is assumed to be unimpacted. Chemical concentrations in impacted vadose zone soil pore water are documented in Table 6.

Exposure Point Concentrations in Soil

Worst-case concentrations of chemicals in onsite soil are calculated in Table 6 under an assumption of equilibrium partitioning between vadose zone pore soil water (with chemical concentrations as calculated in the previous step) and the solid soil phase per Eq. 2.

Onsite commercial/industrial workers are assumed to be exposed to site soils through incidental ingestion and dermal contact across the entire site. Exposure point concentrations of chemicals in soil are therefore calculated as site-wide average concentrations, incorporating areas of impacted soils (at the worst-case concentrations predicted by equilibrium partitioning) and unimpacted soils. As noted above, the assumed site area for the residential evaluation is based on Cal/EPA guidance [22]; however there is no analogous site-area recommendation for commercial/industrial land use. For the commercial/industrial 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 residential building scenario, *i.e.*, 900 m^2. Thus, the site area is assumed to be 3,400 m^2 for the commercial/industrial building based on 2,500 m^2 of building area and 900 m^2 of non-building area. For the commercial/industrial scenario, a smaller non-building site area is conservative for both the soil and groundwater evaluations. Exposure point concentrations of chemicals in onsite soil are documented in Table 6.

Table 6. Chemical concentrations in module leachate, chemical concentrations in vadose zone soil pore water, and equilibrium soil concentrations for commercial office building scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Concentration (C) in SPLP leachate in mg/L	0.069	0.017	Table 2
Annual breakage rate (B)	0.04%	0.04%	[1]
Annual concentration in vadose zone soil pore water (CV) in mg/L	0.0000276	0.0000068	Eq. 1
Soil water-filled porosity (θ_w) (unitless)	0.3	0.3	[13]
Soil dry bulk density (ρ_b) in kg/L	1.5	1.5	[13]
Soil/soil water partitioning Coefficient (K_d) in L/kg	900	75	[13][14]
Equilibrium concentration in Impacted Soil (CS_{eq}) in mg/kg	0.025	0.00051	Eq. 2
Impacted area (IA) in m^2	25	25	Assumption based on 25 1-m^2 downspouts
Site area (SA) in m^2	3400	3400	Assumption based on 25 times the residential building area and the same non-building area as the residential scenario
Building area (A) in m^2	2500	2500	Assumption based on 25 times the

	Pb in c-Si PV	Cd in CdTe PV	Notes
			residential building area
Exposure point concentration in soil (CS) in mg/kg	6.9×10^{-4}	1.4×10^{-5}	Eq. 3

Exposure Point Concentrations in Air

In the commercial office building scenario, emissions of impacted dust are assumed to occur from the 25 1-m^2 areas of impacted soil where the downspout discharges impacted rooftop runoff to the ground surface. For simplicity and conservatism, dust emissions and dispersion are modeled from a single 25-m^2 source. This approach is health-protective since maximum air concentrations downwind of a single large source area are greater than those from widely dispersed sources of equal area. Exposure point concentrations of chemicals in onsite and offsite ambient air (Table 7) are estimated from the modeled worst-case annual-average dust concentration and the exposure point concentrations of chemicals in soil, per Eq. 4.

Table 7. Exposure point concentrations in air in commercial office building scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Equilibrium concentration in impacted Soil (CS_{eq}) in mg/kg	0.025	0.00051	Table 6
Dust flux (g/m^2/s)	0.000000138	0.000000138	[13]
Source type	Area	Area	Ground source
Modeled area source size (m^2)	25	25	Assumption based on 25 1-m^2 downspouts
Source height (m)	0	0	Ground source
Human receptor height (m)	1.5	1.5	Assumption based on approximate breathing zone height
Urban/Rural option	Urban	Urban	Commercial scenario
Choice of meteorology	Full	Full	Default
Terrain	Simple (Flat)	Simple (Flat)	Required for area source modeling [19]

	Pb in c-Si PV	Cd in CdTe PV	Notes
Automated distance array?	Yes	Yes	Assumption
Minimum downwind distance (m)	1	1	Assumption
Maximum downwind distance (m)	10000	10000	Assumption
Maximum 1-hour dust concentration (CD_{hourly}) in µg/m^3	0.1841	0.1841	Modeled result of SCREEN3 [19] based on above parameters
Persistence factor (P) 1-hour to annual-average conversion (unitless)	0.08	0.08	[20]
Annual average concentration of dust in air (CD_{annual}) in µg/m^3	0.0147	0.0147	Eq. 5
Concentration of chemical in air (CA_{annual}) in µg/m^3	3.7×10^{-10}	7.5×10^{-12}	Eq. 4

Exposure Point Concentrations in Groundwater

In the commercial office building scenario, as discussed above, impacted rainfall runoff from the building rooftop is discharged to the ground surface via downspouts. For the purpose of specifying the area of impacted vadose zone soil water which comprises the potential source of groundwater impacts (and for the purpose of determining the appropriate DAF for use in Eq. 6), the source area is the downspout discharge area of 25 m^2. Based on this source area, a 90th percentile DAF is obtained from the USEPA soil screening guidance technical background document [21]. The calculation of exposure point concentrations in groundwater per Eq. 6 is documented in Table 8. The estimate is the same as the residential building scenario because in both cases, downspout discharge limits the impacted area to a small area with the same corresponding DAF value.

Table 8. Exposure point concentrations in groundwater for commercial office building scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Annual concentration in vadose zone soil pore water (CV) in mg/L	0.0000276	0.0000068	Table 6

	Pb in c-Si PV	Cd in CdTe PV	Notes
DAF (unitless)	37600	37600	[21]
Exposure point concentration in groundwater (CW) in mg/L	7.3×10^{-10}	1.8×10^{-10}	Eq. 6

4.4 Utility-Scale Solar Scenario

The estimation of exposure point concentrations of chemicals in soil, air, and groundwater for the utility-scale solar scenario are calculated in accordance with the methodology described in Section 4.1, with scenario-specific input assumptions as noted below.

Chemical Concentrations in Module Leachate and Vadose Zone Soil Pore Water

Chemical concentrations in module leachate are the same for all exposure scenarios (see Table 2).

In the utility-scale solar scenario, it is assumed that the rainwater that falls upon each module runs off the module onto an area of ground surface equal to the module area (2 m^2). This situation is unlike the other product-usage scenarios (residential building, commercial building) where impacted water is discharged to the same ground surface via downspouts, with mixing of impacted and unimpacted water represented by Eq. 1. In the utility-scale solar scenario, there is no downspout mixing and chemical concentrations in vadose zone soil pore water at the locations of PV module breakage are represented directly by SPLP leachate concentrations (Table 9).

Exposure Point Concentrations in Soil

Worst-case concentrations of chemicals in onsite soil are calculated under an assumption of equilibrium partitioning between vadose zone pore soil water (with chemical concentrations as calculated in the previous step) and the solid soil phase, per Eq. 2.

The site area is assumed to be 300 hectares (3,000,000 m^2) based on a 100 MWac facility and 3 hectares per MWac [24]. Assuming a dc:ac ratio of 1.2 and module wattage of 350 Wdc, the site contains approximately 350,000 modules or 700,000 m^2 of modules assuming 2 m^2 per module (17.5% module conversion efficiency). The assumptions on module area and module conversion efficiency are based on approximate characteristics of a 72-cell mono-crystalline silicon solar module [25]. Based on an annual breakage rate of 0.04% and assuming that the rainwater that falls upon each broken module runs off the module onto an area of ground surface equal to the module area, the annual impacted area is 280 m^2.

Onsite commercial/industrial workers are assumed to be exposed to site soils through incidental ingestion and dermal contact across the entire site. Exposure point concentrations of chemicals in soil are therefore calculated as site-wide average concentrations, based on the ratio of impacted soil area to unimpacted soil area.

Table 9. Chemical concentrations in module leachate, chemical concentrations in vadose zone soil pore water, and equilibrium soil concentrations for utility-scale solar scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Concentration (C) in SPLP leachate in mg/L	0.069	0.017	Table 2
Concentration in vadose zone soil pore water (CV) in mg/L			
Soil water-filled porosity (θ_w) (unitless)	0.3	0.3	[13]
Soil dry bulk density (ρ_b) in kg/L	1.5	1.5	[13]
Soil/soil water partitioning coefficient (K_d) in L/kg	900	75	[13][14]
Equilibrium concentration in impacted soil (CS_{eq}) in mg/kg	62.1	1.3	Eq. 2
Annual impacted area (IA) in m^2	280	280	Based on 100 MWac facility (see text) and 0.04% annual breakage rate [1] (see text)
Site area (SA) in m^2	3,000,000	3,000,000	Based on 100 MWac facility (see text)
Building area (A) in m^2	100	100	Assumes on-site operations and maintenance building
Exposure point concentration in soil (CS) in mg/kg	5.8×10^{-3}	1.2×10^{-4}	Eq. 3

Exposure Point Concentrations in Air

In the utility-scale solar scenario, emissions of impacted dust are assumed to occur from the small (2-m^2) areas of impacted soil resulting from release from broken modules. These emissions are conservatively modeled as a single area source with area equal to the sum of the individual module-sized source areas in Table 9 (280 m^2). This approach is health-protective since maximum air concentrations downwind of a single large source area are greater than those from widely dispersed sources of equal area. Exposure point concentrations of chemicals in onsite and offsite ambient air (Table 10) are estimated from the modeled worst-case annual-average dust concentration and the exposure point concentrations of chemicals in soil, per Eq. 4.

Table 10. Exposure point concentrations in air in utility-scale solar scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Equilibrium concentration in impacted soil (CS_{eq}) in mg/kg	62.1	1.3	Table 9
Dust flux (g/m^2/s)	0.000000138	0.000000138	[13]
Source type	Area	Area	Ground source
Modeled area source size (m^2)	280	280	Table 9
Source height (m)	0	0	Ground source
Human receptor height (m)	1.5	1.5	Assumption based on approximate breathing zone height
Urban/Rural option	Rural	Rural	Utility-scale scenario
Choice of meteorology	Full	Full	Default
Terrain	Simple (Flat)	Simple (Flat)	Required for area source modeling [19]
Automated distance array?	Yes	Yes	Assumption
Minimum downwind distance (m)	1	1	Assumption
Maximum downwind distance (m)	10000	10000	Assumption

	Pb in c-Si PV	Cd in CdTe PV	Notes
Maximum 1-hour dust concentration (CD_{hourly}) in µg/m^3	0.878	0.878	Modeled result of SCREEN3 [19] based on above parameters
Persistence factor (P) 1-hour to annual-average conversion (unitless)	0.08	0.08	[20]
Annual average concentration of dust in air (CD_{annual}) in µg/m^3	0.070	0.070	Eq. 5
Concentration of chemical in air (CA_{annual}) in µg/m^3	4.4×10^{-6}	9.0×10^{-8}	Eq. 4

Exposure Point Concentrations in Groundwater

As discussed above, the utility-scale solar scenario comprises impacts assumed to occur from the set of small (2-m^2) areas of impacted soil resulting from release from broken modules. For estimating potential impacts to groundwater, these emissions are conservatively modeled as a single area source with area equal to the sum of the individual module-sized source areas (280 m^2). Based on this source area, a 90th percentile DAF is obtained from the USEPA soil screening guidance technical background document [21].

As further discussed below in Section 6, this evaluation implicitly assumes: 1) a groundwater extraction well is located only 25 feet away from every broken module; and 2) the chemicals released from every broken module are transported to the same groundwater extraction well. In actuality, most broken modules will be further away and only a fraction of the broken modules would be within the capture zone of the extraction well. The calculation of exposure point concentrations in groundwater per Eq. 6 is documented in Table 11.

Table 11. Exposure point concentrations in groundwater for utility-scale solar scenario

	Pb in c-Si PV	Cd in CdTe PV	Notes
Annual concentration in vadose zone soil pore water (CV) in mg/L	0.069	0.017	Table 9
DAF (unitless)	9630	9630	[21]

	Pb in c-Si PV	Cd in CdTe PV	Notes
Exposure point concentration in groundwater (CW) in mg/L	7.2×10^{-6}	1.8×10^{-6}	Eq. 6

5 Comparison of Exposure Point Concentrations to Risk-based Screening Levels

The significance of potential chemical exposures is evaluated through comparison of exposure point concentrations to USEPA residential and industrial risk-based screening levels in soil, air, and water [14] and comparison to USEPA maximum contaminant levels (MCL) in water [14]. Residential screening levels are applicable to the on-site and off-site residential receptors in this evaluation, and industrial screening levels are applicable to the onsite commercial/ industrial worker receptor in this evaluation. The screening levels are based on physical, chemical, and toxicological properties and default residential and industrial exposure assumptions as documented in USEPA risk assessment guidance [11-13][21]. The screening levels account for chronic exposure to chemicals protective of both cancer and non-cancer endpoints.

Exposure point concentrations in soil, groundwater, and air calculated in section 4 are summarized in Tables 12 and 13 for the three exposure scenarios evaluated here, *i.e.*, residential building, commercial office building, and utility-scale solar. Exposure point concentrations in soil and air are compared to the soil and air risk-based screening levels [14]. Exposure point concentrations in groundwater are compared to groundwater risk-based screening levels and maximum contaminant levels (MCLs), which are legal standards that apply to public water systems [14].

As can be seen by examining Tables 12-13 and Figures 3-4, the exposure point concentrations of Pb and Cd in soil, air, and groundwater conservatively calculated here are below the associated risk-based and regulatory screening levels for c-Si PV and CdTe PV for all three scenarios examined. USEPA screening levels are utilized because of their specificity to exposure scenarios (residential and commercial/industrial). These scenarios have different exposure factors such as shorter exposure frequency for a worker (250 days/yr) than a resident (350 days/yr) [14], which can result in higher screening levels for commercial/industrial scenarios than the residential scenario.

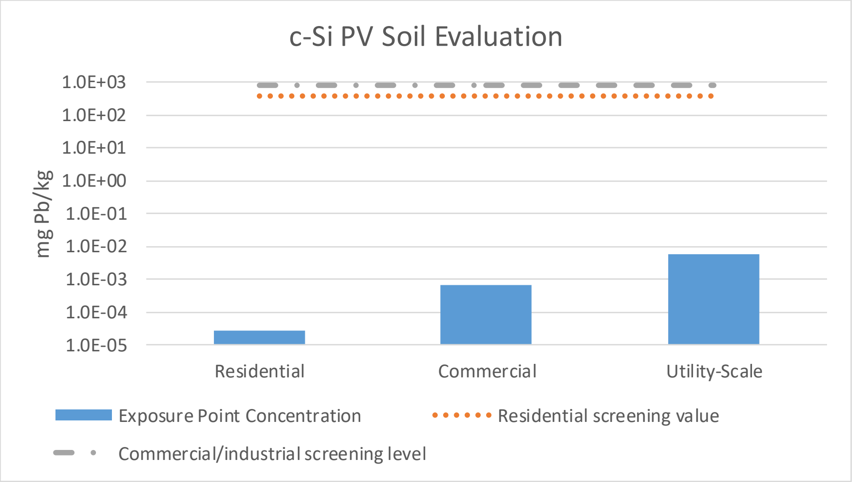
Health screening levels can differ by region. For example, the World Health Organization (WHO) has established water and air screening levels for Pb (0.01 mg/L and 0.5 µg/m^3, respectively) and Cd (0.003 mg/L and 0.005 µg/m^3, respectively) [26][27]. The WHO screening levels are slightly lower than residential screening levels from USEPA for water and slightly higher than residential screening levels from USEPA for air, but within the same order of magnitude. Since the exposure point concentrations of Pb and Cd for c-Si and CdTe PV module breakage, respectively, are several orders of magnitude below USEPA health screening values, they are also below the WHO screening values for water and air.

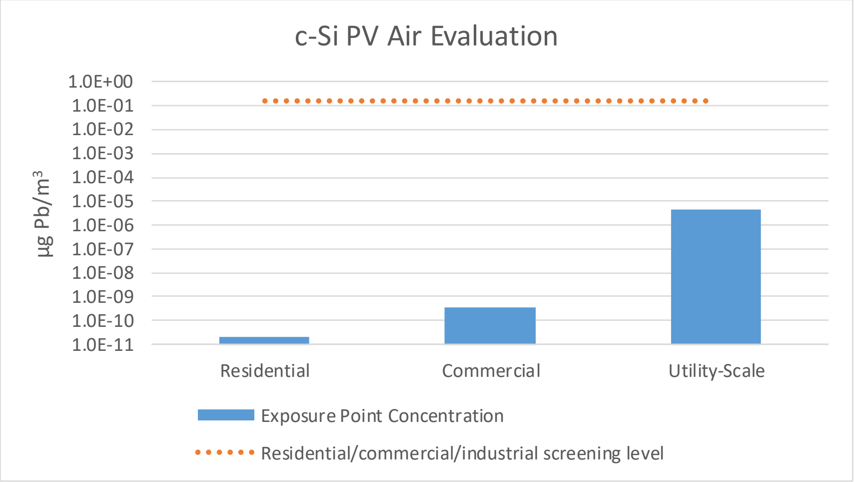
Table 12. Comparison of Pb Exposure Point Concentrations to Risk-based Screening Levels and Maximum Contaminant Levels [14] for c-Si PV

		Soil Evaluation		Air Evaluation		Groundwater Evaluation		
Exposure Scenario	Receptor	Exposure Point Concentration	Risk-based Screening Level	Exposure Point Concentration	Risk-based Screening Level	Exposure Point Concentration	Risk-based Screening Level	Maximum Contaminant Level
Pb for c-Si PV		(mg/kg)	(mg/kg)	(µg/m³)	(µg/m³)	(mg/L)	(mg/L)	(mg/L)
Residential building	Onsite resident	2.8×10^{-5}	4.0×10^{2}	2.0×10^{-11}	1.5×10^{-1}	7.3×10^{-10}	1.5×10^{-2}	1.5×10^{-2}
Commercial office building	Onsite commercial / industrial worker	6.9×10^{-4}	8.0×10^{2}	3.7×10^{-10}	1.5×10^{-1}	Not applicable	1.5×10^{-2}	1.5×10^{-2}
	Offsite resident	Not applicable	Not applicable	3.7×10^{-10}	1.5×10^{-1}	7.3×10^{-10}	1.5×10^{-2}	1.5×10^{-2}
Utility-scale solar	Onsite commercial / industrial worker	5.8×10^{-3}	8.0×10^{2}	4.4×10^{-6}	1.5×10^{-1}	Not applicable	1.5×10^{-2}	1.5×10^{-2}
	Offsite resident	Not applicable	Not applicable	4.4×10^{-6}	1.5×10^{-1}	7.2×10^{-6}	1.5×10^{-2}	1.5×10^{-2}

Table 13. Comparison of Cd Exposure Point Concentrations to Risk-based Screening Levels and Maximum Contaminant Levels [14] for CdTe PV

		Soil Evaluation		Air Evaluation		Groundwater Evaluation		
Exposure Scenario	Receptor	Exposure Point Concentration	Risk-based Screening Level	Exposure Point Concentration	Risk-based Screening Level	Exposure Point Concentration	Risk-based Screening Level	Maximum Contaminant Level
Cd for CdTe PV		(mg/kg)	(mg/kg)	(µg/m³)	(µg/m³)	(mg/L)	(mg/L)	(mg/L)
Residential building	Onsite resident	5.7×10^{-7}	7.1×10^{1}	4.2×10^{-13}	1.6×10^{-3}	1.8×10^{-10}	9.2×10^{-3}	5.0×10^{-3}
Commercial office building	Onsite commercial/ industrial worker	1.4×10^{-5}	9.8×10^{2}	7.5×10^{-12}	6.8×10^{-3}	Not applicable	9.2×10^{-3}	5.0×10^{-3}
	Offsite resident	Not applicable	Not applicable	7.5×10^{-12}	1.6×10^{-3}	1.8×10^{-10}	9.2×10^{-3}	5.0×10^{-3}
Utility-scale solar	Onsite commercial/ industrial worker	1.2×10^{-4}	9.8×10^{2}	9.0×10^{-8}	6.8×10^{-3}	Not applicable	9.2×10^{-3}	5.0×10^{-3}
	Offsite resident	Not applicable	Not applicable	9.0×10^{-8}	1.6×10^{-3}	1.8×10^{-6}	9.2×10^{-3}	5.0×10^{-3}





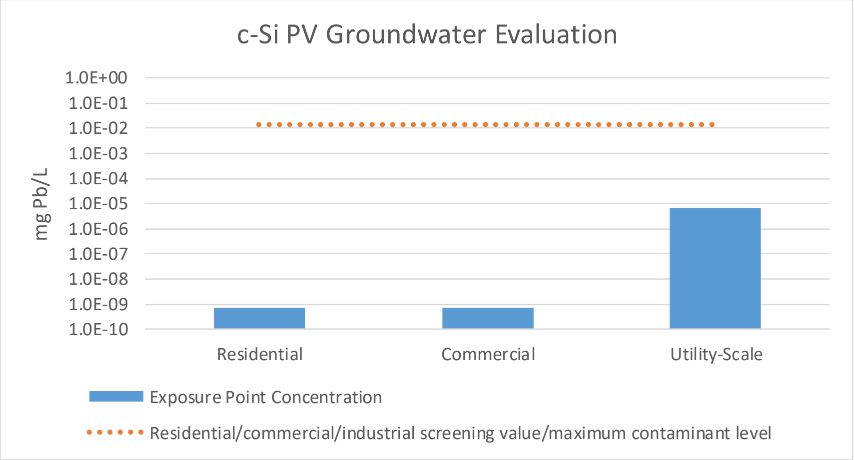


Figure 3. Comparison of Pb exposure point concentrations in soil, groundwater and air to risk-based screening levels and maximum contaminant levels [14] for c-Si PV located on residential rooftops, commercial rooftops and ground-mounted utility-scale scenarios. Note the log scale, where the y-axis spans several orders of magnitude.

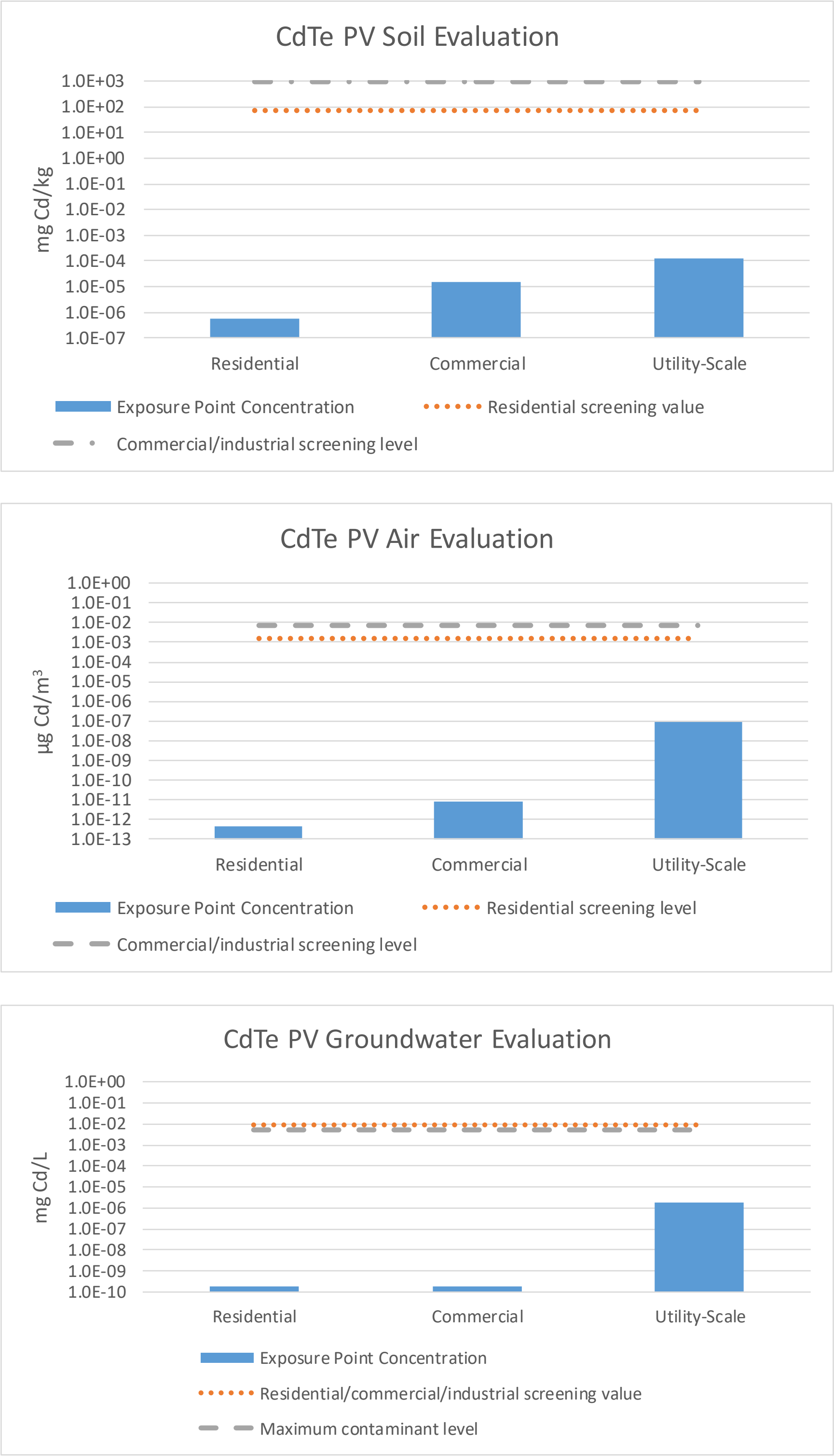


Figure 4. Comparison of Cd exposure point concentrations in soil, groundwater and air to risk-based screening levels and maximum contaminant levels [14] for CdTe PV located on residential rooftops, commercial rooftops and ground-mounted utility-scale scenarios. Note the log scale, where the y-axis spans several orders of magnitude.

6 Uncertainties

Uncertainties related to key modeling parameters contributing to variance (see Table 15) are summarized in Table 14 and further described in the subsections below.

Table 14. Uncertainty in key model parameters

Parameter	Best estimate	Approach in this evaluation
Leachate concentration	Use of stable materials, PV module encapsulation, product durability testing, and operations and maintenance procedures limit the potential for rainwater leaching from broken PV modules.	Leachate concentration is based on standard rainwater leaching test (USEPA Method 1312; Synthetic Precipitation Leaching Procedure).
Breakage rate	Rate of module breakage that remains undetected in the field over exposure duration (1 yr) expected to be negligible given removal of modules broken during installation, routine inspections and/or power output monitoring during operation, and emergency response and cleanup following extreme weather events.	Breakage rate is based on warranty return statistics assuming breakage remains undetected in the field over exposure duration (1 yr).
Soil-water partitioning	Will fluctuate based on frequency and duration of rainfall with limited partitioning in absence of rainfall.	Equilibrium partitioning represents the theoretical maximum concentration possible in the solid phase, for a given concentration in soil pore water.
Transport to groundwater extraction well	Site-specific based on use of groundwater as potable water.	Groundwater extraction well is assumed to be located 25 feet away from all impacted soil areas and chemicals released from every broken module are transported to the same groundwater extraction well.

6.1 Leaching of Chemicals from Broken Modules

The rates at which chemicals are released from a broken module to rainwater are estimated with SPLP test results (Table 2). The SPLP test was conducted on 1 cm module samples, agitated over an 18-hour period in a simulated acidic rainwater solution (H_2SO_4/HNO_3; pH 4.2). Because field breakages mainly consist of fractures in which modules remain intact rather than break into pieces [1], the SPLP extraction provides a larger surface area for contact than the module would likely experience in field conditions.

6.2 Breakage Rate

An annual module breakage rate of 0.04% is assumed based on warranty return statistics. Of these breakages, over one-third occur during shipping and installation and are removed prior to plant operation, and breakage rate declines after the installation and initial operating period.

The exposure scenarios also assume that a broken module would remain undetected and in the field over the exposure duration (1 yr), whereas routine inspections and power output monitoring of commercial and utility-scale PV systems are used to identify modules that are nonfunctioning potentially due to breakage [1]. This is a health protective assumption leading to a likely overestimation of risk.

An example warranty return rate distribution is shown in Figure 5, with higher initial rates during the shipping and installation period and leveling off for the remainder of the service life. Higher breakage rates are possible given extreme weather events, but are also subject to emergency response and cleanup, limiting the likelihood of broken modules remaining undetected in the field over the exposure duration (1 yr). The sensitivity analysis in Section 6.5 accounts for higher breakage rates from extreme weather events using an upper bound breakage rate of 100%.

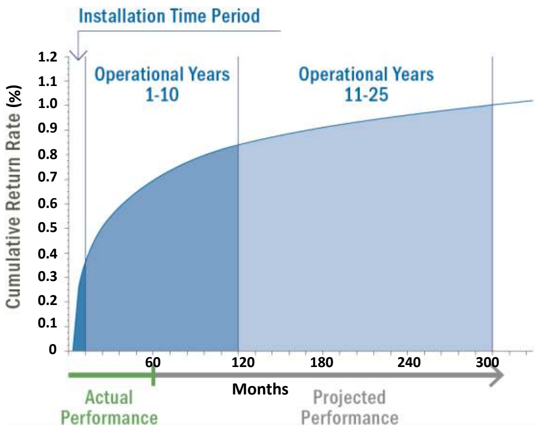


Figure 5. Example warranty return rate as a function of months in service [1]

6.3 Chemical Transport to Soil via Equilibrium Partitioning

Potential soil impacts resulting from the release of chemicals from broken modules are conservatively based on the assumption of equilibrium partitioning of chemicals between vadose zone soil water and soil. The equilibrium concentration represents the theoretical maximum concentration possible in the solid phase, for a given concentration in soil pore water.

This approach does not account for the loss of chemical 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 of chemical available (*i.e.*, the mass that is released from broken modules), 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, however, is based on the initial, higher pore water concentration; the actual equilibrium soil concentration would be lower and would fluctuate over time due to variability in rainfall. Accounting for the loss of chemical mass from the pore water to the solid phase would also lower chemical concentrations in soil water that are assumed to penetrate to groundwater, and so reduce predicted groundwater exposures; thus, the approach is health protective leading to an overestimation of risk.

6.4 Transport to Groundwater

The potential transport of chemicals to groundwater is based on the USEPA DAF model. This model assumes that the groundwater extraction well is located 25 feet away from the edge of the source, *i.e.*, from site-impacted vadose zone soil water. In the utility-scale solar scenario, the potential sources of groundwater impact are the individual broken modules at a 300-hectare site. In this scenario, the actual distance from impacted vadose zone soil water to the offsite groundwater extraction well would be much greater than assumed here for all broken modules, including those adjacent to the site boundary where buffers between adjoining properties typically exceed 25 ft. Furthermore, it is assumed that the chemicals released from every broken module at the site are transported to the same offsite groundwater extraction well. In reality, it is highly likely that only a fraction of the site would be within the capture zone of the offsite extraction well.

6.5 Monte Carlo Uncertainty Analysis

The potential impact of varying the above input parameters on predicted exposure point concentrations can be evaluated through Monte Carlo simulation (n=10,000 runs). Instead of using single point values, the input parameters are varied according to distributions described in Table 15, using Oracle Crystal Ball V. 11.1.2.4.850 software. The concentration in leachate (C) is varied based on a lognormal distribution with mean and standard deviation from SPLP testing [15-17]. Annual breakage rate (B) is varied according to a triangular distribution with a lower bound of 0% and an upper bound of 100%, with a likely value of 0.04% based on warranty return statistics [1]. The soil/soil water partitioning coefficient (K_d) is also varied according to a triangular distribution with values from USEPA [13][14]. The lower and upper bound values for K_d are based on extremes of soil pH (pH 4.5 to 9.0 for Pb and pH 4.9 to 8.0 for Cd). Likely values for K_d are based on central values of soil pH (pH 6.8) utilized in section 4. The dilution-attenuation factors (DAF) for the residential and commercial scenarios are varied according to a triangular distribution representing nationwide DAF values in the U.S. for groundwater extraction wells located 25 feet away from the edge of the source, as documented by USEPA [21]. USEPA guidance provides 85th, 90th, and 95th percentile DAF values. The 90th percentile was used in Section 4 and the wider range of DAF values (85th to 95th percentile) are evaluated in the sensitivity analysis. The 85th, 90th, and 95th percentile DAF values correspond to the lower bound, likely, and upper bound values of the triangular distribution, respectively (Table 15).

In the case of the utility-scale PV scenario, the DAF has the potential for greater variance, both from the range of percentiles (85th to 95th) and from a range of impacted areas (IA) which can vary based on breakage rate. To account for all the possible DAF values, a lognormal distribution is used based on the full range of DAF values from USEPA [21]. In contrast, the residential and commercial scenarios have fixed impacted areas (IA) due to downspout discharge, so a triangular distribution for DAF is used, as previously described. The use of a lognormal distribution for representing concentrations (C) and utility-scale scenario DAF is based on goodness of fit testing (Shapiro Wilk Test Statistic on log-transformed data with USEPA ProUCL V. 5.0 software).

Table 15. Input parameter distributions for Monte Carlo simulation of exposure point concentrations

Exposure Scenario		Distribution Parameters							
PV Technology	System Type	Input Variable	Distribution	Minimum	Mean	Standard Deviation	Likeliest	Maximum	Reference
c-Si PV	Residential, Commercial, Utility-Scale	Concentration (C) in SPLP leachate in mg Pb/L	Log-normal	-	0.069	0.056	-	-	[17]
CdTe PV	Residential, Commercial, Utility-Scale	Concentration (C) in SPLP leachate in mg Cd/L	Log-normal	-	0.017	0.002	-	-	[16]
c-Si, CdTe PV	Residential, Commercial, Utility-Scale	Annual breakage rate (B)	Triangular	0%	-	-	0.04%	100%	[1]
c-Si PV	Residential, Commercial, Utility-Scale	Pb Soil/soil water partitioning Coefficient (Kd) in L/kg	Triangular	4.5	-	-	900	7,640	[14]
CdTe PV	Residential, Commercial, Utility-Scale	Cd Soil/soil water partitioning Coefficient (Kd) in L/kg	Triangular	15	-	-	75	4,300	[13]
c-Si, CdTe PV	Residential	Dilution-attenuation factor (DAF)	Triangular	609.01	-	-	37,600	1,090,000	[21]
	Commercial		Triangular	609.01	-	-	37,600	1,090,000	[21]
	Utility-Scale		Log-normal	-	30,439	164,002	-	-	[21]

Table 16 summarizes how the input parameters which were varied in the Monte Carlo simulation (Table 15) contribute to the variance in the predicted exposure point concentrations in soil, air, and groundwater. For all three media and scenarios, the breakage rate contributes to about half of the variance due to the large range considered (annual breakage rate from 0 to 100%). For soil and air, the soil/soil water partitioning coefficient and concentration in leachate each contribute about one-quarter of the variance for c-Si PV, while the soil/soil water partitioning coefficient contributes about half the variance for CdTe PV. For groundwater, the contribution to variance is similar to soil and air, except that the dilution-attenuation coefficient contributes to the variance instead of the soil/soil water partitioning coefficient. For all three media, the concentration in leachate contributes to less than 1% of the variance for CdTe PV due to the relatively small standard deviation of the SPLP leachate results (Table 15). This variance represents variability from use of a standard leaching test designed to simulate rainwater leaching (USEPA Method 1312; SPLP). As noted in section 3, some previous non-standard leaching tests utilizing finely ground samples and/or extended extraction cycles have resulted in a wider range of leachate concentrations, but do not represent field breakage conditions. The variance in the utility-scale groundwater exposure scenario is primarily due to the DAF, with the full range of USEPA DAF values considered to account for the range of breakage rates, as previously described.

Table 16. Contribution to variance in Monte Carlo simulation of exposure point concentrations.

Exposure Scenario			Contribution to Variance			
PV Technology	System Type	Exposure Point Concentration	Annual Breakage Rate (B)	Dilution Attenuation Factor (DAF)	Soil/soil water partitioning Coefficient (K_d)	Concentration (C) in SPLP Leachate
c-Si PV	Residential	In soil (CS)	47.1%	-	27.0%	25.7%
		In air (CA)	47.1%	-	27.0%	25.7%
		In groundwater (CW)	44.1%	33.0%	-	22.6%
	Commercial	In soil (CS)	48.2%	-	25.7%	25.9%
		In air (CA)	48.2%	-	25.7%	25.9%
		In groundwater (CW)	42.5%	35.2%	-	22.1%
	Utility-Scale	In soil (CS)	48.2%	-	26.5%	25.1%
		In air (CA)	47.6%	-	27.0%	25.3%
		In groundwater (CW)	88.6%		-	11.1%
CdTe PV	Residential	In soil (CS)	53.1%	-	46.2%	0.5%
		In air (CA)	53.1%	-	46.2%	0.5%
		In groundwater (CW)	54.7%	44.6%	-	0.4%
	Commercial	In soil (CS)	52.8%	-	46.6%	0.3%
		In air (CA)	52.8%	-	46.6%	0.3%
		In groundwater (CW)	55.5%	43.3%	-	0.7%
	Utility-Scale	In soil (CS)	54.6%	-	44.9%	0.4%
		In air (CA)	52.0%	-	46.8%	0.8%
		In groundwater (CW)	99.4%		-	0.2%

The results of the Monte Carlo simulation are shown graphically in Figures 6-8, using box-and-whisker plots, where the box indicates the quartiles of the distribution (25th, 50th, and 75th percentiles) and the whiskers indicate the 1st and 99th percentiles. The mean is indicated by the cross. The range of exposure point concentrations in the Monte Carlo simulation is higher than the single point values in Tables 12-13. This is due to the much higher range of breakage rates considered in the Monte Carlo simulation, where the breakage rate accounts for approximately half of the variance (Table 16). Exposure point concentrations of Pb and Cd for c-Si and CdTe PV, respectively, in residential, commercial, and utility-scale systems are below USEPA health screening values in soil, air, and groundwater for both the single point estimates (Tables 12-13, Figures 3-4) and Monte Carlo uncertainty simulation (Figures 6-8).

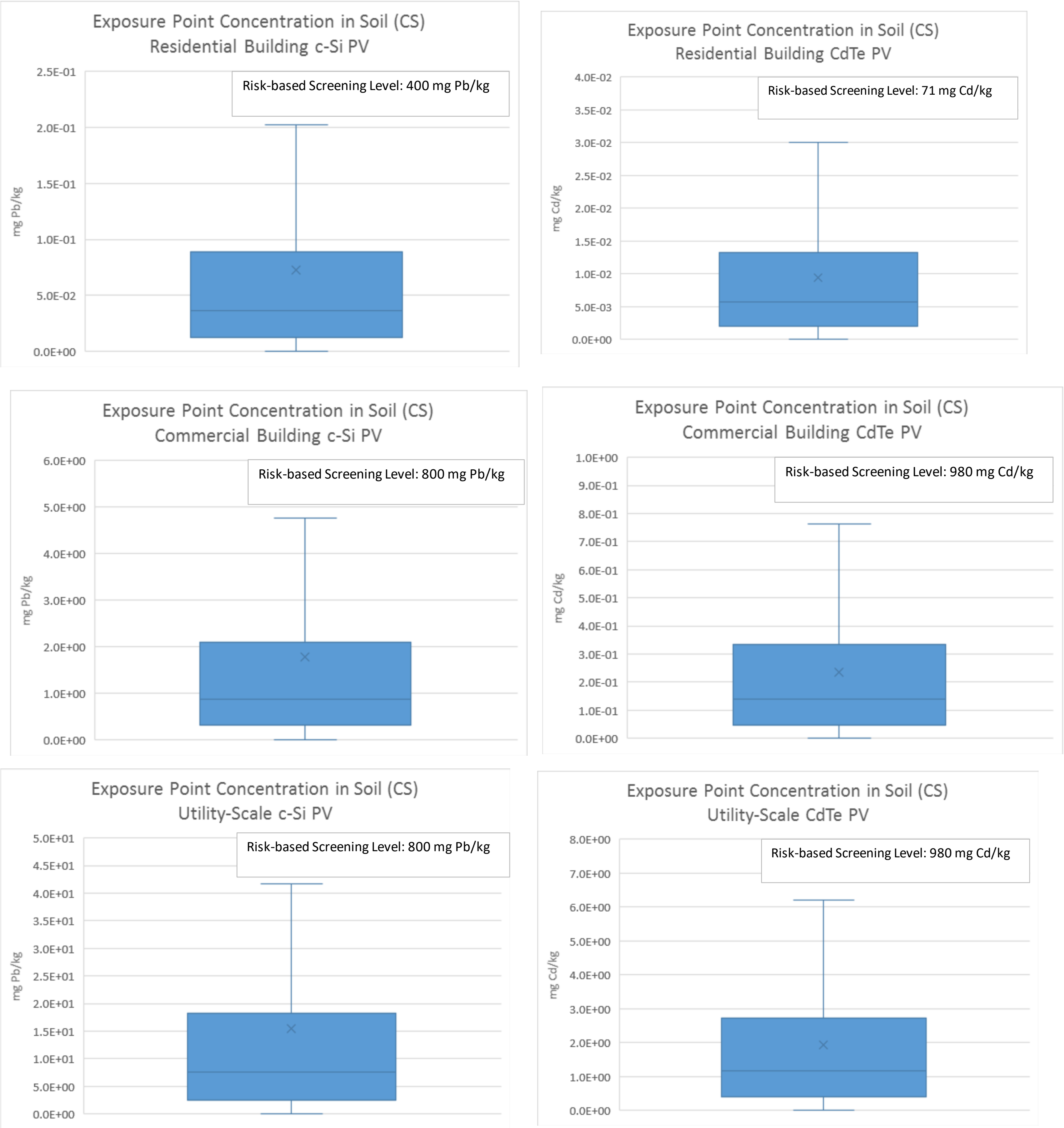


Figure 6. Monte Carlo simulation of exposure point concentration in soil (CS) for c-Si and CdTe residential, commercial, and utility-scale PV systems.

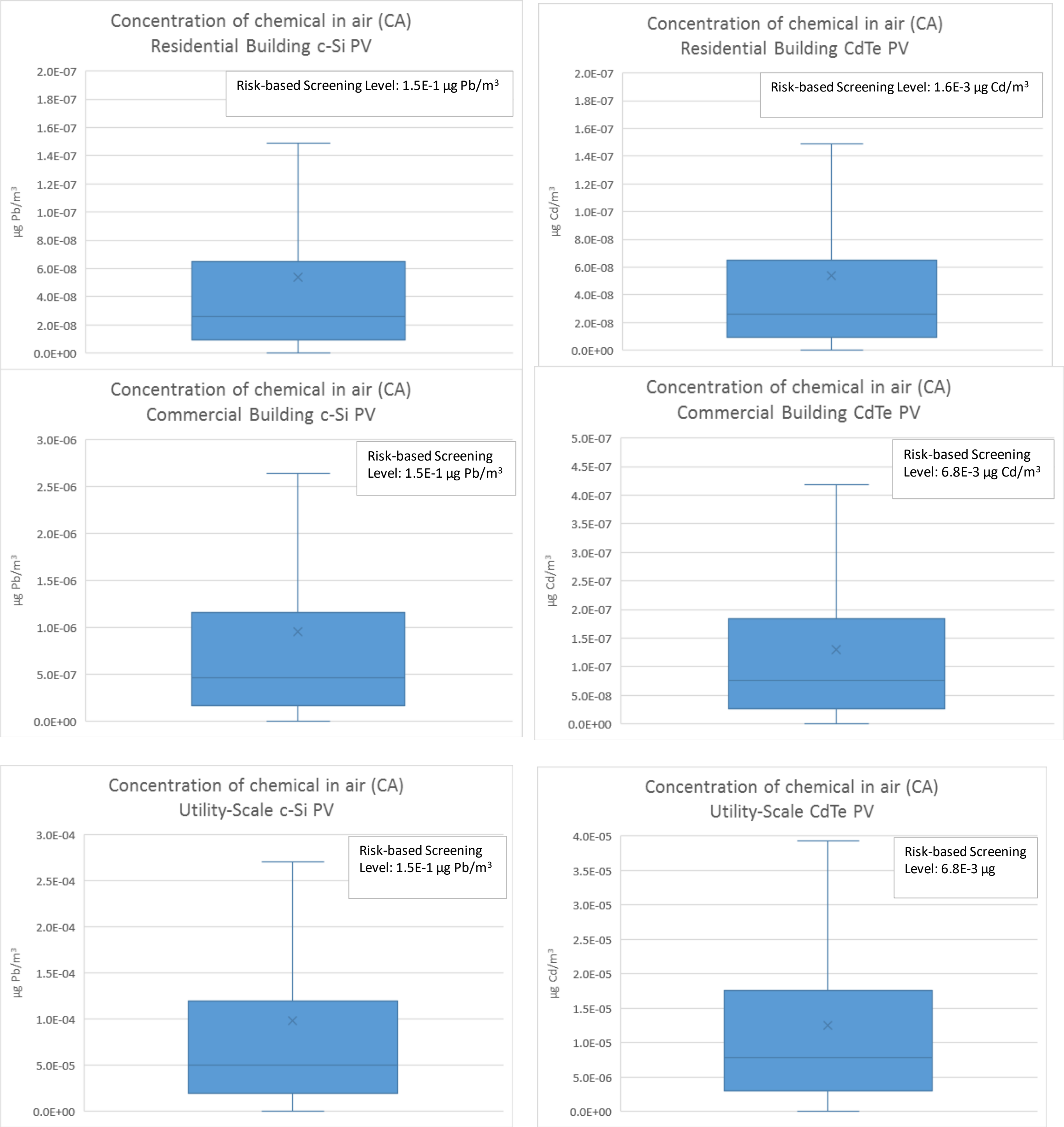


Figure 7. Monte Carlo simulation of exposure point concentration in air (CA) for c-Si and CdTe residential, commercial, and utility-scale PV systems.

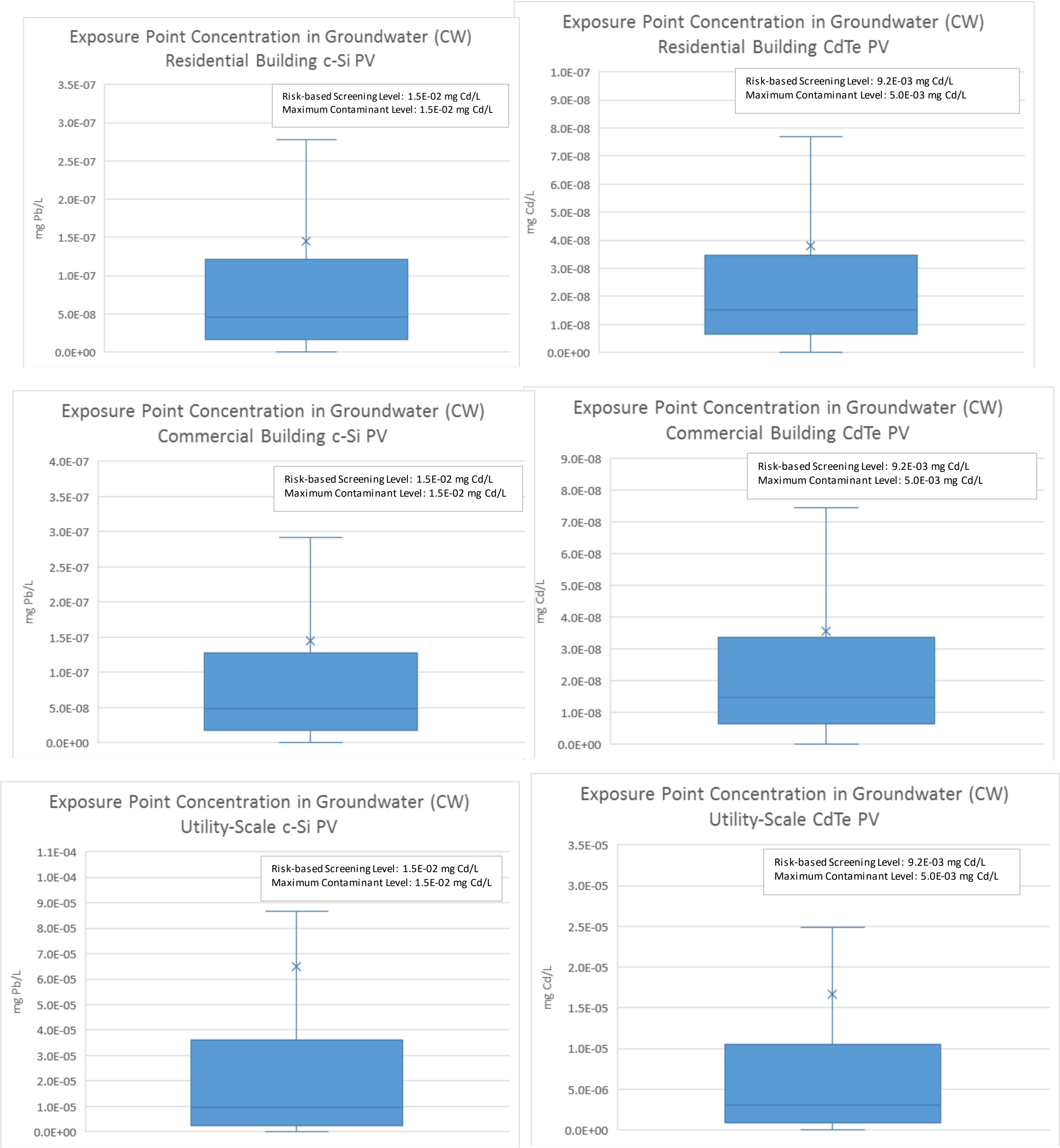


Figure 8. Monte Carlo simulation of exposure point concentration in groundwater (CW) for c-Si and CdTe residential, commercial, and utility-scale PV systems.

7. Summary

This report presents methods for analysis of potential health impacts associated with emissions from field breakage of photovoltaic modules, as demonstrated through analysis for the highest prioritized chemical in each of two commercial PV technologies: Pb content in c-Si PV and Cd content in thin film CdTe PV. The analysis quantifies potential impacts for residential rooftop, commercial rooftop, and utility-scale PV systems. 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.

Screening-level human health risk assessment has been conducted for potential on-site and off-site residential receptors and on-site commercial/industrial worker receptors. Potential health effects are evaluated through a comparison of predicted exposure point concentrations in soil, air, and water with risk-based screening levels published by USEPA. Exposure point concentrations of Pb and Cd for c-Si and CdTe PV, respectively, in residential, commercial, and utility-scale systems are below USEPA health screening values in soil, air, and groundwater for both the single point estimates and Monte Carlo uncertainty simulation. Potential ecological risks have not been evaluated in this report. For a more complete evaluation of the potential health risks from field breakage of PV modules, the methods demonstrated here for Pb and Cd can be applied to other chemicals of potential concern for current or emerging PV technologies.

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