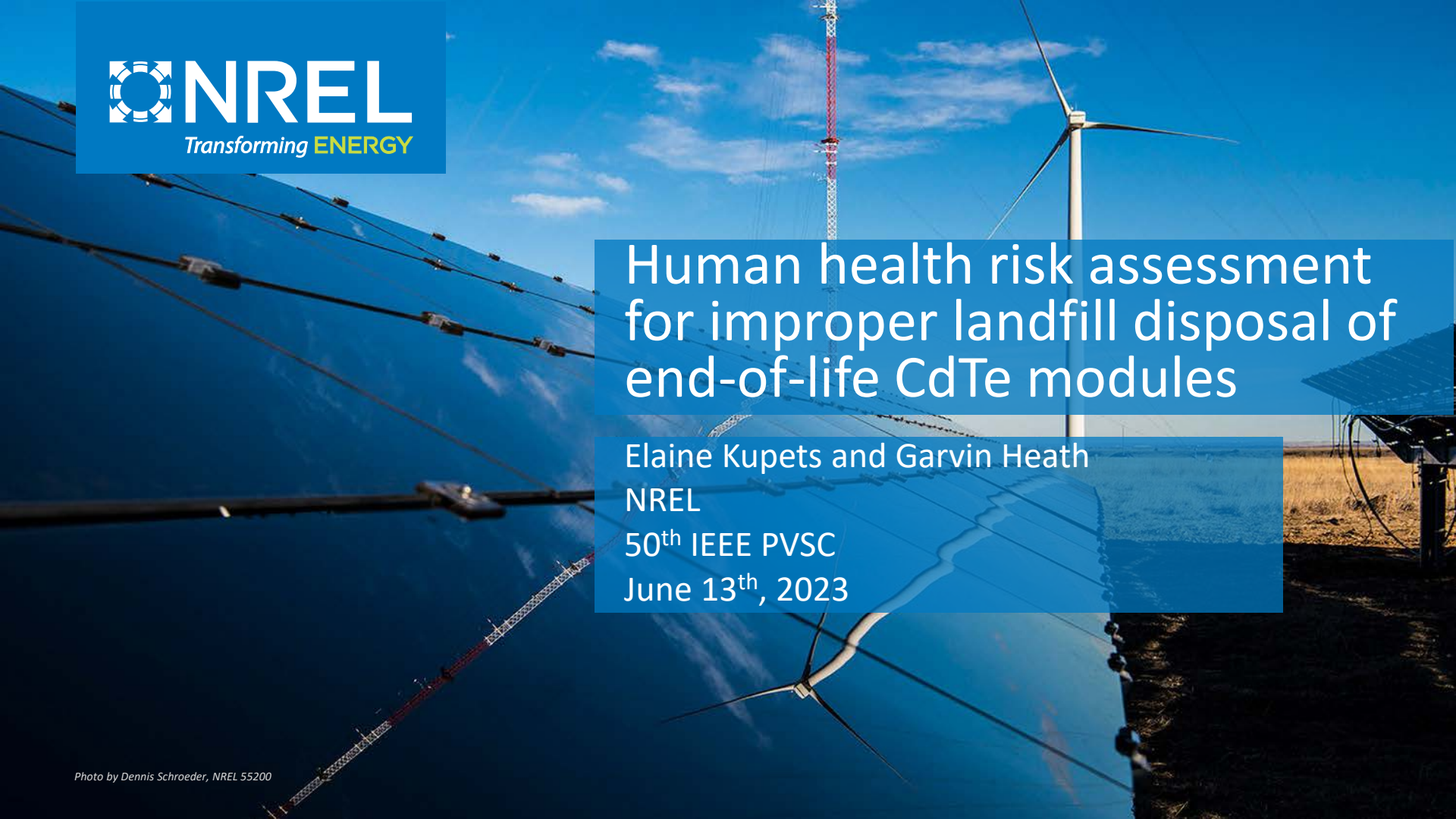

Human health risk assessment for improper landfill disposal of end-of-life CdTe modules

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Photo by Dennis Schroeder, NREL 55200

Outline

1. Introduction to human health risk from landfilling CdTe PV
2. General and case-specific human health risk assessment procedure
3. Collection of data and inputs
4. Methodology to directly estimate cancer risk and non-cancer hazards
5. Findings for potential carcinogenic risks and non-carcinogenic findings
6. Screening-level risk findings
7. Conclusions, future research

Landfilling photovoltaics (PV): A human health risk?

- Stakeholder concerns: Exposure to materials contained within PV modules poses a danger to human health (e.g., lead, selenium, cadmium)
  - Potential human health risk from metals leaching from landfilled end-of-life PV modules?

- Human health risk assessments: Process that evaluates the probability of adverse health effects in humans from exposure to waste in various contaminated environmental media

- Sinha et al. (2019) performed a human health risk assessment (HHRA) on an improper landfilling scenario of PV for multiple PV technologies
  - Analyzed cancer risks and non-cancer hazards of the most likely single constituent that poses the greatest health concerns (lead for c-Si, cadmium for CdTe, selenium for CIGS)

- This study is an extension of the 2019 study, analyzing a complete profile of CdTe PV constituents (**Cd, Se, Te, Cu, Si, Cr, Mo, Sn, Zn, Al, Ni**), 11 in total
  - Most comprehensive HHRA for CdTe PV modules to date of which we are aware

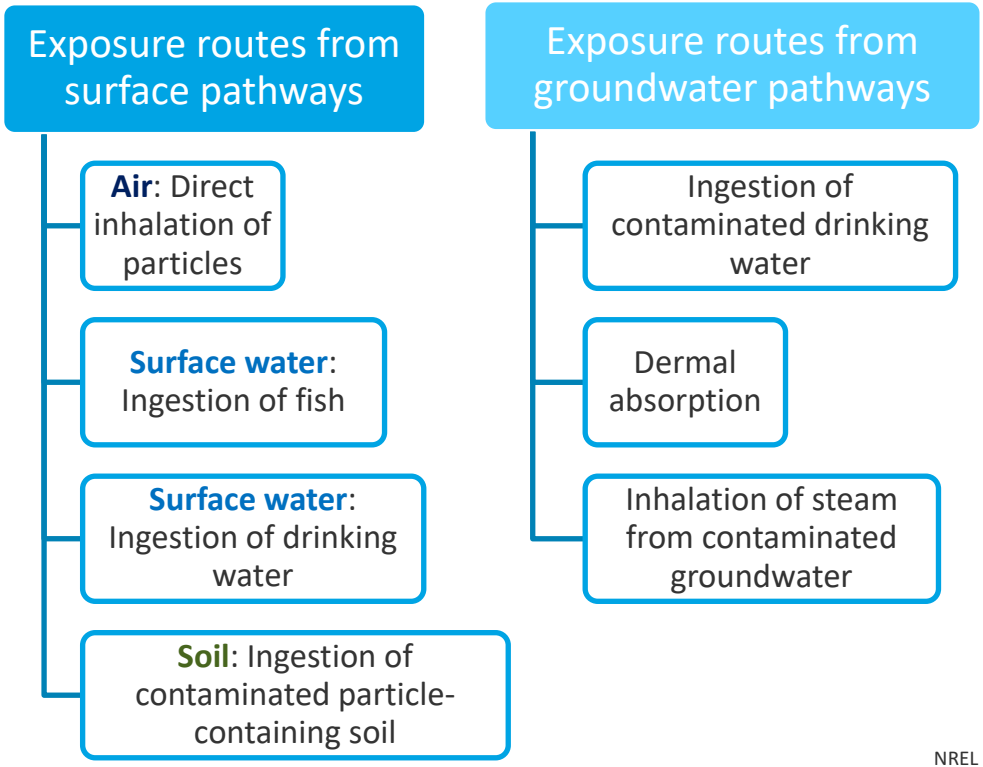
Improper landfill exposure scenario

- Potential cancer risks and non-cancer hazards to an off-site residence from improper 10 MW CdTe PV disposal in an unsanitary landfill
  - "Improper" disposal = use of unsanitary landfills = landfills unlined at the base, allowing leachate to migrate into groundwater and subsurface soils
  - Unsanitary landfills are illegal in the US, "worst-case" scenario

- Following U.S. Environmental Protection Agency (EPA, 1999) and National Research Council (NRC, 1994) guidance on HHRAs, we applied health-protective assumptions representative of an unsanitary landfill throughout the analysis
  - Decrease the likelihood of underestimating carcinogenic risks and non-carcinogenic hazards

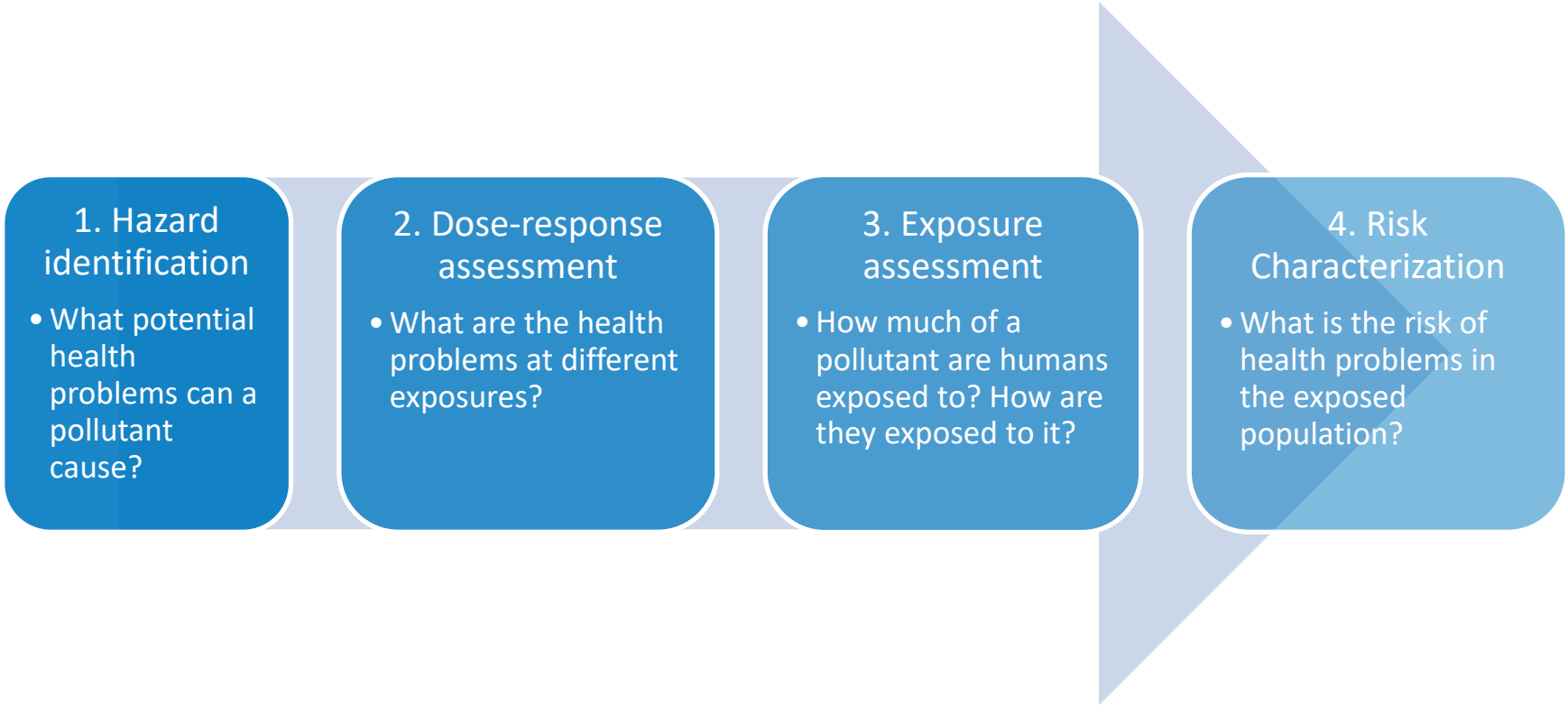
Improper landfill exposure scenario: Pathways

- Exposure from chemicals via groundwater and surface (surface water, soil, air) pathways (Sinha et al., 2019)
  - Pathways = the course PV elements take to reach a human
  - Routes (means of entry into the human body): ingestion, dermal contact, inhalation



General procedure for a human health risk assessment

(as recommended by the National Research Council and USEPA)



Case-specific human health risk assessment procedure

Potential hazard identification

- 11 CdTe PV Constituents: **Cd, Se, Te, Cu, Si, Cr, Mo, Sn, Zn, Al, Ni**

Dose-response function availability

- 1. Elements with available toxicological data
- 2. Elements without available toxicological data

Exposure assessment

- Model potential risks and hazards of a PV element exposure scenario through groundwater and surface pathways

Risk characterization

- 1. Is there a potential cancer risk (sum of all pathways and elements > 1×10^{-6}), and/or potential non-cancer hazard (sum of all pathways and elements > 1)?
- 2. Do exposure concentrations from PV waste surpass regulatory screening-level thresholds unique to each element and exposure pathway, thereby signifying potential adverse human health effects?

Method

- 1. DRAS software
- 2. Screening concentration calculations

Data and human health risk assessment inputs

- Conducted a literature review screening for the following:
  - Find field-representative (crushed, landfilled CdTe PV module) samples to obtain leachate data for the HHRA, as proposed by TamizhMani et al. (2021)
    - Eliminated studies that used milled or finely ground samples
  - Use current First Solar Series 6 module data (incomplete data supplemented with Series 3 module proxy data)
- Quantify element-specific parameters for the HHRA: Toxicity Characteristic Leaching Procedure (TCLP) values (mg/L), chemical concentration (mg/kg), waste volume (m^3)

Element	Proxy data or Series 6 data?	# of datasets	TCLP values (mg/L)	Element chemical concentration per module (mg/kg)		Waste volume for modules (m^3)	Available for DRAS input?
				median	maximum		
Cd	Series 6	7	0.2 – 0.6 (median = 0.42)	649	649	400	**yes**
Se	Series 6	7	N.D.**	61.0	61.0	400	**yes**
Te	Series 6	7	N.A.**	638	638	400	no
Cu	Series 6	7	N.A.	250	250	400	**yes**
Si	Series 6	7	N.A.	8300	8300	400	no
Cr	Series 6, proxy	1	N.D.	180*	180*	500*	**yes**
Mo	proxy	1	N.A.	500*	500*	500*	**yes**
Sn	proxy	3	N.A.	22.6*	45.0*	500*	**yes**
Zn	proxy	1	N.A.	0.002*	0.002*	500*	**yes**
Al	proxy	3	N.A.	51.4*	100*	500*	no
Ni	proxy	1	N.A.	1.20*	1.20*	500*	**yes**

* Indicates proxy data
** N.D. is defined as “Not Detected”, while N.A. is defined as “Not Available”

Directly estimating potential carcinogenic risks and non-carcinogenic hazards: Delisting Risk Assessment Software (DRAS)

USEPA developed and approved for regulatory use (USEPA 2008). DRAS performs fate and transport and exposure assessment modeling for all identified pathways to calculate potential human health risks associated with improperly landfilling 10 MW of Series 6 CdTe modules.

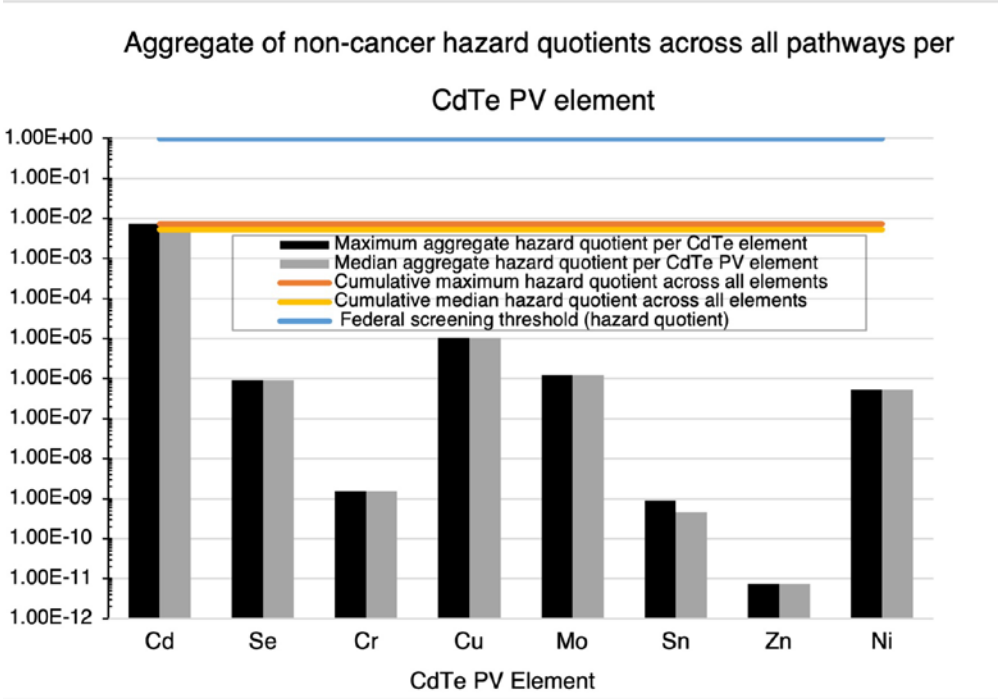
Assigned default target cancer risk index of 1×10^{-6} and target non-cancer hazard index of 1 (common thresholds for federal delisting determinations).

Requires dose-response toxicological values which exist for eight of the eleven CdTe PV elements (**Cd, Se, Cu, Cr, Mo, Sn, Zn, Ni).**

DRAS results: Potential cancer risk and non-cancer hazard

- Potential cancer risk was found for only Cd and Ni (risk quotients of **3.27x 10^{-9}** and **9.14 x 10^{-13}** respectively), and through only one exposure route: inhalation of particles
  - Aggregate of cancer risk from both elements are 3 orders of magnitude below regulatory threshold
    - Consistent with Sinha et al. (2019) for Cd
  - Only these two elements of the entire profile had available toxicological data with values greater than zero pertaining to this pathway

- Potential non-cancer hazards were quantified for all 8 DRAS elements across all pathways (see graph)
  - Aggregate hazard quotient across all pathways for all elements was several orders of magnitude (~10^3) below the threshold of 1



Screening-level risk findings

- To estimate potential human health effects for the three elements where cancer risks and non-cancer hazards could not be directly estimated (as followed in Sinha et al. (2019)):
  - Back-calculated exposure point concentrations from given USEPA HHRA model equations in groundwater, surface water, ambient air, and soil exposure pathways
  - Results were compared against federal regulatory screening levels (USEPA risk-based screening levels) unique to each element

- Findings:
  - Estimated exposure point concentrations are lower than the screening thresholds in every case where a screening level was available (34 cases for the 11 evaluated elements)
  - Ranking of chemical concentrations and TCLP values had a direct correlation to exposure point concentration
    - **Si** had the highest exposure concentrations for surface water, air, and soil pathways (greatest chemical concentration)
    - **Cd** had the highest exposure concentration for the groundwater pathway (greatest/sole TCLP values)

Limitations and Uncertainties

1. USEPA Delisting Risk Assessment Software: only 8 of 11 CdTe elements could be directly evaluated for potential cancer risks or non-cancer hazards due to lack of toxicological data available.

2. Proxy data substitutions led to overestimation of input parameters such as waste volume (the module size for the proxy data is 25% larger than the current module we aimed to study (Series 6).

3. Exposure point concentrations: overestimations in input parameters led to overestimation of calculated exposure point concentrations.

4. Not all pathways for each element had a toxicological risk-based screening level.

Conclusions

1. Despite data limitations that led to overestimation in input parameters and/or results, all 11 CdTe PV elements tested with available toxicological data were below USEPA cancer risk and non-cancer hazard thresholds.
   a. An alternative method of risk screening came to the same conclusion.

2. We followed NRC/EPA procedures and found USEPA risk thresholds pertaining to this exposure scenario were not exceeded. Thus, in the context of current data limitations, our research indicates that human health risk from landfilling CdTe PV modules is considered *de minimis*.
   a. If more data become available, our study could be updated or expanded.

3. Cadmium poses the greatest human health cancer risk and non-cancer hazard of elements tested in a First Solar Series 6 CdTe PV module.

4. Although our results strongly suggest that landfilling CdTe PV modules are not hazardous to health (utilizing best available data and methods), implementing material recovery efforts such as recycling over disposal is preferred, to support recovery of valuable and critical materials that can offset future manufacturing materials demand.

Future research and implications

1. Completion of human health risk assessments of not just CdTe, but all major PV technologies, is contingent upon available PV module data and progress in expanding toxicological data relevant to federal regulatory threshold determinations.

2. As PV efficiency improves, less PV materials will be used per MW of installed capacity. Thus, future PV projects equivalently sized to current projects (e.g., 10 MW) but with less module mass will pose less of a health risk.

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