



Calculation of immissions in case of fire in a photovoltaic system made of cadmium telluride modules



Fig. 1: Typical Fire Damages of a Photovoltaic System¹

1 Introduction and Objective

The effects of thin-film modules made of cadmium telluride (CdTe modules) on the environment are often discussed by the general public and by experts. These discussions concern the following:

- The effects of a fire on the neighborhood and the general public
- The possible input of pollutants into the soil and ground water (e.g., due to water used for extinguishing the fire or destruction of the modules by hail)
- Disposal of the photovoltaic modules (PV modules)

¹ no CdTe modules

Based on VDI guideline 3783, this information bulletin solely considers the effects of CdTe modules on the neighborhood and the general public in the case of fire. To this end, the expected emission concentrations were calculated depending on the distance to the fire site, and the results were compared with the evaluated results for the corresponding air pollutants.

In VDI guideline 3783, sheet 1, a calculation method is described for estimating the distribution of releases "caused by accidents", which is based on the Gaussian distribution formulas. Using this calculation model, the average and least favorable distribution situations can be recorded and emission concentrations can be determined from the source site at a range between 100 m and 10,000 m.



Fig. 2: Schematic depiction of a photovoltaic module fire with fire gas emissions and typical immission concentration curve dependent on the distance to the fire site.

2 General Information

A photovoltaic system is composed of several solar modules. A distinction is made based on the materials used, for example:

- silicon-based modules (e.g., monocrystalline, polycrystalline, amorphous)
- Modules based on semi-conductor components (e.g., cadmium telluride (CdTe), copper indium diselenide (CIS), copper indium gallium diselenide (CIGS))
- New technologies (e.g., organic solar cells, dye solar cells)

While crystalline silicon cells, for example, are designated as "thick-film technology" of the 1st generation, semiconductor cells, amorphous silicon cells and a few of the new technologies are classified as "thin-film cells" of the 2nd and 3rd generation.²

² Branchenorientierte Dialoge zur Entwicklung von Leitmärkten der Ressourceneffizienz auf der Basis von integrierten Technologie Roadmaps, Abschlussbericht zur Arbeitspaket 9, hier Roadmap AP 9.5: Ressourceneffiziente Photovoltaik 2020+, Materialeffizienz und Ressourcenschonung (MaRess) – Projekt im Auftrag des BMU/UBA, <u>http://ressourcen.wupperinst.org/downloads/MaRessAP95AbschlussBer.pdf.</u> S. 84

Silicon-based PV modules dominate the global market. However, the share of thin-film modules based on semiconductors is increasing. The share of CdTe modules within thin-layer technology was approx. 60% in 2009.³

3 PV modules containing cadmium

Depending on the thin-film technology, cadmium compounds can exist in two different forms:

- As cadmium telluride (CdTe)
- As cadmium sulfide (CdS).

CdTe modules contain compounds made of CdTe and CdS, while CIS and CIGS modules might only contain CdS compounds depending on the manufacturer.⁴

Note that cadmium does not exist as a metallic component in PV modules, but instead as a cadmium compound in the cited forms.

3.1 CdTe

According to a study requested by the German Environment Ministry⁵, CdTe modules contain between 6.55 g cadmium/m² and 66.4 g cadmium/m² with an average value of approx. 14 g cadmium/m². Cadmium concentration in the semi-conductor layer is approx. 50%. Modules of the globally leading manufacturer contained 20 g CdTe/m² and 1.7 g CdS/m², corresponding to approx. 10 g cadmium/m² at that point in time.

According to a newer study requested by the Federal Ministry for the Environment (BMU), Nature Conservation and Nuclear Safety, a typical Cd Te module (120 cm x 60 cm) contains 18 g CdTe/m² and 0.483 CdS g/m² and consequently fewer than 7 g cadmium per module. The thickness of the CdTe layer of typical modules is approx. $7 \mu m$.⁶

3.2 CdS

Consequently, the CdS share in the CdTe/CdS modules is substantially lower than the CdTe share. At < 0.1 μ m the CdS layer is also considerably thinner than the CdTe layer.

CIS modules can contain cadmium sulfide. The contents are between 0.2 and 0.45 g/m²; corresponding to 0.002 weight percentage of CdS.⁷ CIGS modules can also contain between 0.2 and 0.24 g/m² CdS depending on the manufacturer.⁸

3.3 Structure of CdTe modules

While crystalline Si modules only have a front glass pane, semi-conductor layers in thin-film modules are enclosed frameless between two glass plates (front and supporting glass). Consequently, the relative portion of glass is generally higher in thin-film modules than in crystalline modules.

³ http://www.energie-und-technik.de/erneuerbare-energien/news/article/27654/0/Photovoltaik-

Markt waechst 2010 staerker als erwartet/?cp=0&action=taf form

⁴ Stoffbezogene Anforderungen an Photovoltaikprodukte und deren Entsorgung, Ökopol, Endbericht 15.01.2004, S. 25, <u>http://www.umweltdaten.de/publikationen/fpdf-l/2789.pdf</u>

⁵ Stoffbezogene Anforderungen an Photovoltaikprodukte und deren Entsorgung, Ökopol, Endbericht 15.01.2004, S. 72, <u>http://www.umweltdaten.de/publikationen/fpdf-l/2789.pdf</u>

⁶ Studie zur Entwicklung eines Rücknahme- und Verwertungssystems für Photovoltaische Produkte, Ökopol, et al, November 2007, S. 46, http://www.pvcycle.de/fileadmin/pvcycledocs/documents/publications/StudiePVCycleDownload17de270808.pdf

⁷ Stoffbezogene Anforderungen an Photovoltaikprodukte und deren Entsorgung, Ökopol-Endbericht, 15.01.2004, S. 24

⁸ Studie zur Entwicklung eines Rücknahme- und Verwertungssystems für Photovoltaische Produkte, Ökopol, November 2007, S. 42

3.4 **Properties and classification of CdTe**

Under normal condition, CdTe is a black, odorless, crystalline powder. It is a non-flammable solid and is practically insoluble in water. The melting point of the compound is 1,041° C.⁹

In accordance with Directive (EG) No. 1272/2008¹⁰ on the classification, identifying and packaging of materials and compounds, CdTe is classified as H302 (injurious to health when swallowed), H312 (injurious to health when in contact with skin), H332 (injurious to health when inhaled), as well as H400 (very toxic for water organisms) and H410 (very toxic for water organisms with long-term effect).

4 Distribution calculation for pollutants from CdTe modules

4.1 General information

Effects caused by fire for the neighborhood and the general public, which can result via an air pathway, are to be investigated using the following distribution calculation. As a rule, the type and quantity of the fire gases that are caused depend on the respective material properties and the existing fire conditions.

In addition to fire gases typical for a building fire (CO, CO₂, NO_x, etc.), the following cadmium and/or telluride fire gases can be released during fires of photovoltaic modules containing CdTe under certain conditions (e.g., high fire temperature and destruction of the glass plates with corresponding release of compounds containing cadmium):

- Cadmium fumes
- Metallic oxide fumes (CdO, TeO₂)

The effects of such a fire are evaluated by comparing the respectively determined emission concentrations with the relevant evaluation values of the individual fire gases.

4.2 Marginal parameters

The distribution for the CdTe modules was calculated according to VDI 3783, sheet 1, and was performed using the computer program STOER V2.23 (R. Röckle, TÜV Umwelt GmbH, Freiburg, 1994). The following assumptions were made for a worst case scenario:

- The CdTe layer is exposed completely and temperatures are reached at which cadmium is released.
- The emission time is 15 minutes.
- The source height¹¹ is 8 m.
- The test point height¹² is 1 m.

⁹ GSBL – Datenbank (Gemeinsamer Stoffdatenpool Bund Länder); <u>www.gsbl.de</u>

¹⁰ Verordnung über die Einstufung, Kennzeichnung und Verpackung von Stoffen und Gemischen, <u>http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ: L:2008:353:0001:1355:de:PDF</u>

¹¹ The source height is the height of the roof the modules are installed on.

- Calculations are performed for source dimensions (area of the burning CdTe modules) from 50 m², 500 m² and 1,000 m² at various heat emissions.
- The concentration data are provided for the worst-case distribution situation (wind speed 1 m/s) depending on the distance from the source site.
- The cadmium contents of the modules are between 6.55 and 66.4 g Cd/m². The average value is 14 g Cd/m² PV module.
- A 100% reaction is assumed for the determined emission concentrations.

Additional input parameters for the STOER V2.23 program according to VDI 3783:

- Light gas with lift force
- Roughness class: 3

A continual emission source is assumed for the calculation.

The distribution calculation according to VDI 3783, sheet 1, considers the thermal lift force of the hot combustion gases only after heat input greater than 6 MW, so that the calculated 6 MW fire (without thermal lift force) results in high pollutant emission concentrations in the immediate critical area.

At a lower calorific value with wood at $H_U = 17.28$ MJ/kg, a mass burning rate of 0.35 kg/s results during a 6 MW fire. If 1 kg wood/s burns as fire load under the PV modules, then a fire with a heat input of 17.3 MW results. Consequently, higher heat input is to be expected with an increased area of PV modules and depending on the duration of the fire. As a result, calculation of lower heat input was not performed for larger areas.

Selected heat emissions are derived from literature¹³ for the specified burn-off speeds of wood (193 – 288 kW/m²).

The distribution calculations were performed for the following cadmium contents in the modules:

Case 1: 14.0 g Cd/m² (average cadmium contents in CdTe modules)

Case 2: 66.4 g Cd/m² (maximum value)

Fire areas of three different sizes were considered each time (50 m^2 , 500 m^2 and 1,000 m^2).

¹² The test point height is the immission point's height (calculation point) above ground level.

¹³ Baulicher Brandschutz im Industriebau, Beuth-Kommentare, Kommentar zu DIN 18230 und Industriebaurichtlinie, Hrsg. DIN Deutsches Institut für Normung e. V., AGB Arbeitsgemeinschaft Brandsicherheit, Schneider/Max, Bruchsal, Beuth Verlag GmbH, 3. aktualisierte und überarbeitete Auflage 2003, S. 169.

5 Calculation results

5.1 Case 1: Cadmium contents 14 g/m², fire area 50 m², 500 m² and 1,000 m²

Tab. 1/2: (Case 1) Cadmium contents: 14.0 g/m², fire area: 50 m² PV module

Heat input 6 MW		
Distance [m]	Cd concentration [mg/m ³]	
100	0,05	
200	0,02	
500	0,01	
1000	0,01	

Heat input 10 MW		
Distance [m]	Cd concentration [mg/m ³]	
100	0,03	
200	0,02	
500	0,01	
1000	0,004	

Tab. 3/4: (Case 1) Cadmium contents: 14.0 g/m², fire area: 500 m² PV module

Heat input 60 MW		
Distance [m]	Cd concentration [mg/m ³]	
100	0,09	
200	0,05	
500	0,02	
1000	0,01	

Heat input 100 MW		
Distance [m]	Cd concentration [mg/m ³]	
100	0,05	
200	0,03	
500	0,01	
1000	0,01	

Tab. 5/6: (Case 1) Cadmium contents: 14.0 g/m², fire area: 1,000 m² PV module

Heat input 60 MW		Heat input 200 MW	
Distance [m]	Cd concentration [mg/m ³]	Distance [m]	Cd concentration [mg/m ³]
100	0,15	100	0,04
200	010	200	0,03
500	0,04	500	0,02
1000	0,01	1000	0,01



Fig. 3: Depiction of cadmium immission concentrations depending on the distance from the fire site with average cadmium contents of 14.0 g/m² (Case 1).

¹⁴ AEGL-2 values, see explanation point 6.1

5.2 Case 2: Cadmium contents 66.4 g/m², fire area 50 m², 500 m² and 1,000 m²

Heat input 6 MW		
Distance [m]	Cd concentration [mg/m ³]	
100	0,21	
200	0,10	
500	0,04	
1000	0,01	

eat input 6 MW

Heat input 10 MW		
Distance [m] Cd concentration [mo		
100	0,16	
200	0,08	
500	0,03	
1000	0,002	

Tab. 7/8: (Case 2) Cadmium contents: 66.4 g/m², fire area: 50 m² PV module

Tab. 9/10: (Case 2) Cadmium contents: 66.4 g/m², fire area: 500 m² PV module

Heat input 60 MW		
Distance [m] Cd concentration [mg/		
100	0,41	
200	0,25	
500	0,09	
1000	0,03	

Heat input 100 MW		
Distance [m]	Cd concentration [mg/m ³]	
100	0,23	
200	0,15	
500	0,06	
1000	0,03	

Tab. 11/12:

(Case 2) Cadmium contents: 66.4 g/m², fire area: 1,000 m² PV module

Heat input 60 MW		Heat input 200 MW	
Distance [m]	Cd concentration [mg/m ³]	Distance [m]	Cd concentration [mg/m ³]
100	0,66	100	0,16
200	042	200	0,16
500	0,16	500	0,08
1000	0,07	1000	0,04



Fig. 4: Depiction of cadmium immission concentrations depending on the distance from the fire site with average cadmium contents of 66.4 g/m² (Case 2).

6 Evaluation

6.1 Evaluation values

The AEGL or ERPG values are generally used for evaluation values of air pollution.¹⁵ These values are peak concentration values based on toxicological science and are provided for each of three different severity degrees of effects.

AEGL-1/ERPG-1	Threshold to noticeable feeling of indisposition
AEGL-2/ERPG-2	Threshold to irreversible effects or other severe, long-lasting health effects or effects preventing flight from the scene
AEGL-3/ERPG-3	Threshold to life-threatening or deadly effect

AEGL values are provided for various exposure times (10 min., 30 min., 1 hour, 4 hours, 8 hours), while ERPG values are only applicable for an exposure time of one hour.

If no AEGL or ERPG values are published, the respective PAC-2 values can be used.¹⁶ PAC values are based on AEGL, ERPG or TEEL¹⁷ values.

The AEGL-2 or ERPG-2 value is normally used to judge whether there is a serious danger for the neighborhood or general public.

6.1.1 Evaluation values for cadmium

The following AEGL-2 values have been published for cadmium:

Exposure time 10 min	1,4 mg/m ³
Exposure time 30 min	0,96 mg/m ³

Because the calculated emission concentrations refer to cadmium, they can be compared directly (without conversion) with the corresponding AEGL value.

6.1.2 Evaluation values for CdO and TeO2

No AEGL or ERPG values have been published for CdO and TeO₂. The PAC-2 value of CdO is 4 mg/m³, and that of TeO₂ is 31.3 mg/m³.

To evaluate the CdO immission concentration, the determined cadmium immission concentrations in the Tables 1 -12 must be multiplied by a factor of 1.14 (emission factor: 1.14 g CdO/g cadmium) to obtain the CdO concentrations. Then this value can be compared with the PAC-2 value of CdO.

When it is assumed that nearly the same quantity relations of cadmium and telluride are in a PV module, the same immission calculation depicted above can be used, based upon the same source strength of both materials. To obtain the immission concentration of TeO₂, the determined concentrations in the Tables 1 - 12 are to be multiplied by a factor of 1.25 (emission factor: 1.25 g TeO₂/g Te).

¹⁵ AEGL: Acute Exposure Guideline Levels; <u>http://www.epa.gov/oppt/aegl/index.htm</u>

ERPG: Emergency Response Planning Guidelines; http://www.aiha.org/insideaiha/GuidelineDevelopment/ERPG/Pages/default.aspx

¹⁶ PAC: Protective Action Criteria; <u>http://www.atlintl.com/DOE/teels/teel.html</u>

¹⁷ TEEL: Temporary Emergency Exposure Limits

6.2 Discussion of results

Comparison of the immission concentrations with the corresponding evaluation values AEGL-2/PAC-2 demonstrates that the evaluation values for the listed cases fall short (see Figures 3 and 4).

The calculation variants show in detail that the total of released cadmium would result in immission concentration of 0.05 mg/m^3 of pure cadmium fumes when there are, for example, cadmium contents of 14.0 g/m^2 , a fire area of 50 m^2 and heat input of 6 MW at a distance of 100 m to the emission site. Comparison of these calculated values with the evaluation values (AEGL-2 (10 min.) of cadmium = 1.4 mg/m^3 in this case) shows that this evaluation value falls short by a considerable degree.

The highest determined value is – as expected – in a fire with the largest area $(1,000 \text{ m}^2)$ with the maximum cadmium module contents (66.4 g/m²) and at the shortest calculable distance (100 m) from the emission site. However, the calculated immmission concentration of cadmium (0.66 mg/m³) is still substantially below the corresponding evaluation value of cadmium.

It should also be noted that it is assumed in the calculations that all cadmium contained in the module is released completely from the CdTe compound as cadmium fumes. Reaction with CdO or a possible diffusion of cadmium in the molten glass was not considered in determining the cadmium immission concentrations. A study on fire investigations of customary CdTe modules, which were heated to temperatures ranging from 760° C to 1,100° C, typical for fires in residences and service buildings, showed that more than 99% of the cadmium remained within the molten glass matrix.¹⁸

Based on thermal conversion processes, it is consequently to be assumed that only a small share of cadmium converts to pure cadmium while other parts convert to CdO, or as CdTe or CdS are not converted. In this case, the corresponding evaluation values fall short by a considerably greater degree.

Because the corresponding evaluation values of CdO and TeO₂ are larger than the evaluation value cadmium, these are substantially fallen short of at a distance of 100 m to the source site.

The following listed aspects also demonstrate that the calculations performed are based on extremely conservative assumptions:

• The calculation method VDI 3783, sheet 1, results in higher immissions compared to other calculation methods¹⁹ and can be described as an extremely conservative model.

¹⁸ Fthenakis, V. et al (2005): Emissions and Encapsulation of Cadmium in CdTe- PV Modules During Fires. Progress in Photovoltaics: Research and Applications, <u>http://onlinelibrary.wiley.com/doi/10.1002/pip.624/pdf</u>

¹⁹ z. B. LASAT (Lagrange-Simulation von Aerosol-Transport)

- The assumption of a longer emission duration would result in a lower source strength and consequently lower immission concentrations.
- The assumed maximum CdTe content (66.4 g/m²) only exists from one manufacturer, and it is substantially lower at other manufacturers and newer CdTe modules.
- In reality, not all PV modules would necessarily be destroyed in the event of a fire.
- In reality, not all CdTe layers would necessarily be exposed completely in the event of a fire.

Even given these extremely conservative and almost unrealistic assumptions, the corresponding evaluation values for pure cadmium immissions as well as for the metallic oxide compounds CdO and TeO₂ fall substantially short at the calculated distances, starting from 100 m from the source site.

6.3 Conclusion

The distribution calculations carried out show that, from a technical standpoint, a serious danger for the immediate neighborhood and general public can certainly be excluded when modules containing CdTe burn.

7 Additional Information

Bavarian Environmental Protection Agency (2011): Pollutants in cases of fire, <u>http://www.lfu.bayern.de/umweltwissen/doc/uw 15 brandereignisse.pdf</u>. UmweltWissen, 12 pages

Bavarian Environmental Protection Agency (1995): Evaluation of fires involving plastics, http://www.lfu.bayern.de/luft/doc/kunststoffbraende.pdf. 54 pages

Bavarian Environmental Protection Agency (2010): Disposal of PV systems, <u>http://www.izu.bayern.de/faq/detail faq.php?pid=0501020100299</u>. Information Center for Environment and Economy (IZU),

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