Assessment of the Risks Associated with Thin Film Solar Panel Technology

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Virginia Center for Coal and Energy Research (MC 0411)
Randolph Hall, Room 133
460 Old Turner Street
Virginia Tech
Blacksburg, Virginia 24061
Phone: 540-231-5038
Fax: 540-231-4078

Report Authors

The primary author for this report is William Reynolds, Jr., Professor, Department of Materials Science and Engineering, Virginia Tech; contributing author is Michael Karmis, Stonie Barker Professor, Department of Mining and Minerals Engineering & Director, Virginia Center for Coal and Energy Research (VCCER), Virginia Tech.

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Contents

1 Summary

This report reviews the environmental risk profile of utility-scale cadmium telluride (CdTe) photovoltaic installations with relevant information from the scientific literature and an audit of the manufacturing and recycling facilities of a domestic manufacturer. Current photovoltaic technologies are described, and the environmental and health issues associated with CdTe are identified. Solubility measurements, bioavailability, acute aquatic toxicity, oral and inhalation toxicity, and mutagenicity studies all confirm CdTe has different physical, chemical, and toxicological properties than Cd. The CdTe compound is less leachable and less toxic than elemental Cd. The risks to the environment arising from broken solar panels during adverse events are considered by reviewing experimental results, theoretical worst-case modeling, and observational data from historical events. In each case considered, the potential negative health and safety impacts of utility-scale photovoltaic installations are low. The need for end-of-life management of solar panels is highlighted in the context of recycling to recover valuable and environmentally sensitive materials. Based upon the potential environmental health and safety impacts of CdTe photovoltaic installations across their life cycle, it is concluded they pose little to no risk under normal operating conditions and foreseeable accidents such as fire, breakage, and extreme weather events like tornadoes and hurricanes.

2 Background

The *2018 Virginia Energy Plan*, required under Virginia Code § 67-201, was released by Governor Northam on October 2, 2018. The plan emphasizes that the legislature has supported:

- 5,000 megawatts (MW) of utility-owned and utility-operated wind and solar resources deemed in the public interest
- 500 MW of rooftop solar resources that are less than 1 MW in size deemed in the public interest
- $1.1 billion investment in energy efficiency programs by investor-owned utilities, and
- Cost recovery structures for projects that modernize the grid and support the integration of distributed energy resources.

The Plan also noted: “Given the economic development opportunities in the solar sector, solar energy has significant room to grow in the coming years. The Solar Energy Industries Association projects that solar energy will grow by an additional 2,293 MW over the next five years.”

The Plan also discussed commitments to utility-scale and distributed solar resources and recommended that: "Governor Northam should double the Commonwealth's 8 percent renewable energy procurement target to 16% by the end of 2022. This target would facilitate the construction of an additional 110 MW of utility-scale and distributed renewable energy resources. In accomplishment of this target, the Commonwealth should complete both on-site PPAs and off-site utility-scale solar and wind projects."

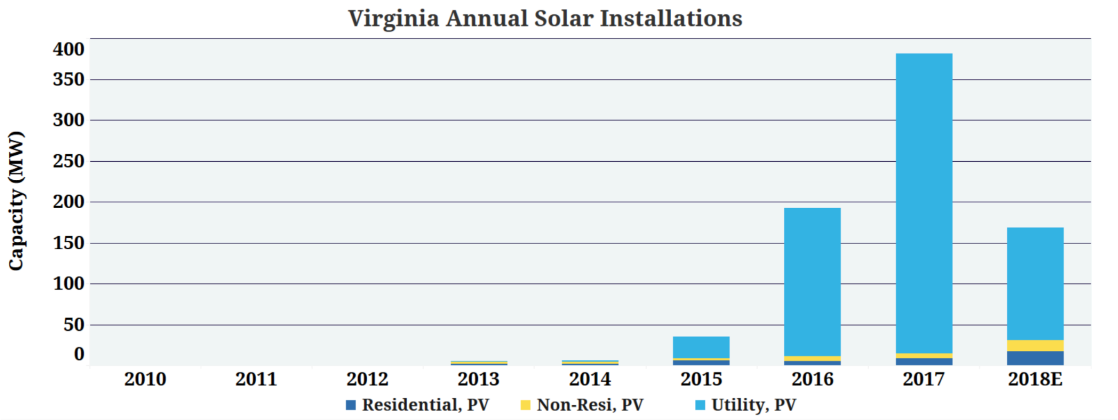

Figure 1: Virginia photovoltaic installation forecast [1].

Since utility-scale photovoltaic installations (solar facilities) are a relatively new component of Virginia's energy infrastructure (Figure 1), the public needs to be informed about potential impacts of the technology on communities. Multiple economic and technological factors must be considered to design and build a solar facility. The case for selecting a particular electric generation technology is usually made with a technique called life-cycle assessment. The technique considers environmental impacts associated with the "cradle-to-grave" stages of a power facility's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

A life-cycle assessment compiles a list of the energy and material inputs used in the life of the power generation facility, considers releases of materials that affect the environment, and evaluates the potential costs associated with the inputs and releases. Life-cycle assessments are sensitive to assumptions built into the underlying model, but they can help incorporate indirect costs into the planning and design of a facility. When considering electrical energy generation, life-cycle assessments for non-fossil fuel based energy sources — such as nuclear, wind, solar, hydro-power — tend to have lower impacts from factors such as greenhouse gases, fine particulates, and eutrophication (harmful enrichment of nutrients to water bodies), but they exert environmental pressure through factors like land occupation, and demand for materials in limited supply [2, 3, 4, 5, 6, 7, 8, 9].

2.1 Purpose and Scope

This report reviews available risk assessments for cadmium telluride (CdTe) semiconductor materials used in the construction of thin film photovoltaic solar technology under consideration for Virginia solar facilities. The review is based upon a survey of technical literature and an audit of the manufacturing and recycling facilities of one domestic manufacturer of CdTe solar panels.

2.2 Photovoltaic Technologies

Technologies for converting solar energy directly into electrical energy, called photovoltaic or PV systems, have evolved rapidly over the past several decades. Commercial photovoltaic systems developed over this period may be grouped into three categories. First generation photovoltaics rely on crystalline silicon (c-Si) in either a single crystal or polycrystalline form to convert solar radiation to electric current. Second generation photovoltaics employ a thin film material such as amorphous silicon (a-Si), multi-junction amorphous and polycrystalline silicon, cadmium telluride (CdTe), copper indium diselenide or disulphide (CIS), or copper indium gallium diselenide/disulphide (CIGS) to do the energy conversion. Third generation photovoltaics add solar concentrators and trackers to the system and may use other semiconductor materials for the conversion process [4]. Each technology has specific strengths and weaknesses, and the overall driver behind all these technologies is the need to reduce the energy cost for consumers. The energy return is often couched in terms of parameters like the "energy payback time," which represents the time needed for a particular technology to produce the energy used to manufacture, install, operate, and decommission it [4].

Weather also plays an important role in the economy of photovoltaic technologies. Solar insolation (a measure of solar strength), temperature, and relative humidity are weather-related factors that impact the energy production of a solar facility. Insolation affects the amount of primary energy available for conversion to electricity, temperature influences the conversion efficiency of the photovoltaic semiconductor, and humidity affects the energy spectrum that falls on the solar panels. The solar insolation for Virginia is roughly halfway between the low values found in the northeast United States and the peak values found in the deserts of the American southwest. Virginia's temperature and humidity are both fairly high. Given these weather-related factors, the leading utility-scale photovoltaic technology is arguably thin film CdTe photovoltaics [10]. For this reason, the remainder of this report will focus on this technology.

3 CdTe Thin Film Photovoltaics

The upper portion of Figure 2 shows an array of CdTe thin film photovoltaic modules on fixed mounts. The number of panels in the array determines the energy generating capacity of the system. The lower portion of Figure 2 is a schematic cross-section through a CdTe photovoltaic module illustrating its internal layers. The central CdTe semiconductor layer is quite thin, as can be seen from the size comparison in the figure between the CdTe film thickness and the thickness of human hair, a blood cell, and the semiconductor layer of silicon photovoltaic devices. The front and back of a CdTe photovoltaic module are glass sheets that transmit the incoming light and protect the internal components. The internal layers provide a semiconductor junction that converts solar radiation to electrical energy and conduction paths to collect the electrical current and connect it to external circuitry.

Figure 2: A CdTe photovoltaic system (top), and a schematic cross-section of a CdTe photovoltaic module (bottom). For comparison, the central CdTe layer is thinner than the thickness of the corresponding semiconductor layer in a silicon photovoltaic device, or the diameter of a red blood cell, or the thickness of human hair. Image source: First Solar, Inc.

3.1 Environmental and Health Issues

Some stakeholders have raised environmental and health concerns with thin film photovoltaic installations because of the use of cadmium compounds in the semiconductor thin film. Cadmium (Cd) is a heavy metal that has adverse effects on human health [11]. Cadmium occurs naturally in soil; the average concentration in Virginia soils is 0.15 mg of Cd/kg soil [12]. Common contributors of cadmium to the environment from human activity are the combustion of coal for power generation and the application of commercial fertilizers for agriculture. Human exposure to cadmium is higher for smokers than non-smokers [13]. Once dissolved in water, Cd can be incorporated into the tissue of crop plants [14] and make its way into the food chain.

Given the potential impact it poses on crops, one approach to assessing environmental hazards of Cd is to estimate the extent to which Cd contamination increases the Cd concentration of soil. For example, this strategy has been used to estimate that the Cd expelled during combustion at a 3000 MW coal-fired power plant deposits 0.00002 mg of Cd/kg soil over the land adjacent to the power plant [15]. A similar approach has been used to show that fertilizing soil with Cd-rich municipal sewage sludge may increase the Cd content of soil by 10 to 15% [12].

In analogous fashion, a simple mass balance (that ignores chemical differences between CdTe and Cd) suggests extracting the Cd contained in a typical CdTe thin film photovoltaic module and mixing it with the underlying soil could increase the concentration of Cd by an amount similar to that expected from fertilizing with municipal sludge. However, using this approach to assess the environmental risk from photovoltaic systems of CdTe is fundamentally flawed for two reasons: (1) it treats the toxicity of cadmium telluride as equivalent to that of cadmium without recognizing the significant chemical differences between the two [16, 17], and (2) it misrepresents the ways in which CdTe photovoltaic solar panels interact with the environment [18].

First, the environmental risks of CdTe and Cd cannot be assumed to be equivalent because the two substances are not chemically interchangeable. To draw a simple analogy, the properties of water (H_2O) are not similar to those of hydrogen gas (H_2) just because the two species both contain hydrogen. Just as it is improper to assume water can burn because hydrogen burns, it is invalid to treat CdTe as if it were as toxic as Cd.

The chemical difference between cadmium telluride and cadmium is partially reflected in their different physical properties. Cadmium telluride has a high melting point (1092°C) relative to that of elemental cadmium (324°C) and tellurium (449°C) [16]. The much higher melting point of CdTe reflects a strong chemical affinity of Cd for Te (bond strength > 5 eV) and the chemical stability of this compound [16]. In qualitative terms, cadmium and tellurium bind strongly to each other, so the cadmium in a CdTe molecule is less chemically available to react with other chemical species. For this reason, the toxicity of CdTe is expected to be different from that of elemental Cd, and CdTe also may have very different accessibility to the environment than Cd. These qualitative interpretations are borne out by experiments. Solubility measurements, bioavailability, acute aquatic toxicity, oral and inhalation toxicity, and mutagenicity studies all confirm CdTe is considerably less toxic than Cd [19, 20].

Second, with regard to the way CdTe interacts with the environment, a life-cycle analysis of CdTe photovoltaics with a focus on capturing cadmium flows and cadmium emissions into the environment [18, 21] compared the 'input' of cadmium to the environment from the CdTe photovoltaic life-cycle with the inputs from a variety of other Cd sources including coal-fired power plants and Ni-Cd batteries. A significant proportion of all Cd released to the environment comes from the emissions of zinc smelting (Cd is produced as a byproduct of zinc refining). This Cd release arises regardless of whether or not it is used in an application.

In photovoltaic module manufacturing, life cycle emissions of heavy metals are primarily associated with indirect emissions from fossil fuel electricity consumption [21]. The actual manufacturing process for CdTe photovoltaic modules directly releases a negligible amount of Cd to the environment because the electrodeposition or vapor transport processes used to produce CdTe thin films require high-purity conditions and tight industrial control. All the Cd consumed in the production of CdTe thin films either ends up in the deposited film or it is recycled. The aforementioned life-cycle analyses [18, 21] also noted Cd is not released during the normal operation of photovoltaic modules. Aside from the potential of environmental CdTe release from damaged panels (considered in Section 3.3.1) or during panel decommissioning (considered in Section 4), the production of CdTe photovoltaic panels would have the consequence of *reducing* the net environmental release of Cd [22] because it diverts Cd from the waste stream of zinc refining operations to CdTe production which then reduces the amount of Cd that ends up in landfills [18].

3.2 CdTe Photovoltaic Module Testing and Reliability

As just noted, there is no risk of CdTe release to the environment as long as the photovoltaic modules are operating normally. The best way to ensure a CdTe photovoltaic system functions reliably is to start with a fault-tolerant design, use robust components, and evaluate system performance through frequent testing. Based upon an audit of First Solar's CdTe photovoltaic manufacturing facility in Perrysburg OH, these objectives can be achieved by using automated statistical process control throughout the entire production process [23]. A battery of electrical, static and dynamic loading, hail impact, thermal and humidity cycling, and light response tests are typically used to assess the reliability of manufactured panels [24]. Standardized tests are used to varying degrees by manufacturers across the photovoltaic industry and include UL 1703/IEC 61215/IEC 61730 certification testing, Long-Term Sequential Test, Atlas 25+ Certification, IEC 62804 Potential Induced Degradation-Resistant Certification, IEC 60068 Certification Desert Sand Resistance, and durability benchmarking by the Fraunhofer PV Durability Initiative.

At the system level, the quality of a utility-scale solar installation's electrical, mechanical, and energy yield can be certified by independent oversight agencies such as the VDE Testing and Certification Institute [25]. Many solar facilities also employ real-time tracking of energy yield with a granularity down to the level of a small number of connected panels. This level of monitoring makes it practical to identify photovoltaic panel failures and their location as soon as they occur. Real-time monitoring helps ensure panels that become damaged by adverse events like storms are located immediately and quickly repaired or taken out of service. This kind of pro-active monitoring is important to maintain the energy yield of an installation, but it also mitigates the environmental risk of CdTe release from broken modules.

3.3 Adverse Events

The approach used in this report to assess potential risks from adverse events is to review: (*i*) experimental results, (*ii*) theoretical worst-case modeling, and (*iii*) observational data from historical events.

3.3.1 Field Breakage

Several assessments of the risks associated with the leaching of CdTe from broken photovoltaic modules are available. There are data from experiments simulating the exposure of broken modules to rain, there is worst-case total release modeling, and there are studies of the loss of metals from shredded photovoltaic modules (crystalline silicon and thin film types).

The fate of CdTe in broken solar module pieces subjected to rainfall was tested by Steinberger [26], who found no critical increase in soil Cd concentrations after 1 year of leaching in an outdoor experiment with actual rainwater. Also, tests in Japan subjected modules with 1 to 5 cracks to a quantity of simulated acid rain (pH 5) equivalent to 40 days of average rainfall; these experiments produced elution concentrations below Cd drainage and waste criteria [27].

In worst-case total release modeling, the extent of Cd leaching from broken CdTe modules in rainwater has been explored under different scenarios [28], and Cd concentrations were predicted to fall well below conservative human health screening levels [28].

A study by Tammaro [29] demonstrated that tumbling shredded photovoltaic modules in water for a day caused water to pick up detectable concentrations of most of the metals found in the original solar panels (Al, Pb, Sb, Ag, Cd from crystalline silicon solar panels and Al, Cr, Cd, Te, Se, Cu, Pb from thin film solar panels). However, it is not clear how the leaching behavior of a tumbled aggregate of centimeter-sized pieces relates to solar panels broken in service.

When photovoltaic modules break in the field, they crack but remain intact. Encapsulation of the module components is achieved through the use of a glass-laminate-glass design (Figure 2). The encapsulation bond strength is on the order of ~ 50 kg/cm^2 making it very difficult to separate the front and back of the module. For example, in a landfill experiment, photovoltaic 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 [30].

Furthermore, under the normal operation of a solar facility, system performance monitoring and routine visual inspection ensures non-functioning modules are detected and promptly removed from the field [31], so even when breakage occurs, long-term exposure to rain is not a likely scenario. Nevertheless, the leaching of a variety of metals from shredded panels [29] demonstrates the need for responsible end-of-life management for all solar technologies (see Section 4 below).

3.3.2 Fires

The fate of CdTe in solar modules subjected to a fire was tested by Fthenakis et al. [32]. By heating sections of a double-glass CdTe solar module to 1100°C, these investigators simulated degradation of a solar panel on the roof of a burning building (a building fire can reach higher temperatures than those expected around ground-mounted modules in a grass or brush fire). The simulated building fire softened the front and back glass panels which quickly joined and encapsulated the CdTe thin film. The glass essentially sealed all the CdTe, and prevented it from volatilizing and escaping.

Using a different approach that assumes total release of more than four times the amount of CdTe contained in today's modules, a large fire area, and the shortest distance from the emission site, the Bavarian Environmental Protection Agency used a computational method with an analytical model to conclude, "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" [33]. Thus, the fate of CdTe in photovoltaic modules in simulated fires and the predicted dispersal of CdTe by analytical models suggest CdTe cleanup following a fire should be straightforward with standard methods.

3.3.3 Storms

Experience with severe storms suggest solar facilities are relatively resilient against high winds and flooding. The following events provide case studies of storm-induced damage to CdTe photovoltaic installations and storm related environmental risks.

April 2015 A tornado struck the Desert Sunlight Solar Farm in the Mojave Desert of California. Of the installation's 8,800,000 photovoltaic modules, 154,843 modules were damaged by the tornado (1.8%). The damaged panels were collected, approximately 135,000 were recycled, and the remainder were disposed of. Sampling of soil and module pieces from the tornado event passed Toxicity Characteristic Leaching Procedure tests, and an environmental non-governmental agency contacted the U.S. Bureau of Land Management and reported no indication of soil contamination. *Link: Desert Sunlight Tornado Damage*.

September 2017 Hurricane Maria (category 5, maximum wind speed of 175 mph) struck the Sonnedix Horizon facility (Salinas Solar Park) in Puerto Rico and caused minor damage to the photovoltaic modules. Of the installation's 167,832 modules, only 872 were damaged (0.52%). *Link: Status Report After Hurricane Maria*.

September 2018 Hurricane Florence (category 4, maximum wind speed of 130 mph) struck the Carolinas causing minimal damage to the solar facilities of Duke Energy and Strata Solar, the two largest solar power operators in North Carolina, with over 20 facilities utilizing CdTe photovoltaics. Only one site experienced wind damage: 12 modules were damaged out of a total of more than 600,000 modules (0.002%). *Link: Minimal Damage After Hurricane Florence*.

October 2018 Hurricane Michael (category 4) struck Florida causing no damage to the solar facility of GameChange Solar in Tallahassee FL. *Link: GameChange Solar Systems Emerge Unscathed from Hurricane Michael*.

Only a small number of modules were damaged in each of the hurricanes noted. Consequently, the documented hurricanes did not cause any release of CdTe to the environment. Damage from the California tornado in 2015 was more serious, but even with the larger number of broken panels, environmental tests demonstrated CdTe was not released into the environment.

4 End of Life Management

At the end of the 25 to 30 year service life of the solar panels in a utility-scale photovoltaic installation, a significant volume of solar panels must be decommissioned, disposed of, or recycled. It was recognized at least a decade ago that large solar facilities presented unique challenges and opportunities for recycling photovoltaic modules [34]. One challenge is that the semiconductor material, CdTe, is a very small fraction of a thin film photovoltaic module ($\sim 0.1\%$ by weight), but it still must be extracted to provide raw material for future thin film photovoltaic module production. Because of the small quantity and low solubility of semiconductor material and the module encapsulation, the modules are characterized as federal non-hazardous waste at end-of-life using the Toxicity Characteristic Leaching Procedure [31].

Unlike spent consumer electronics and batteries which are small and widely distributed, utility-scale photovoltaic panels at the end of their service life are centrally located at solar facilities. This makes photovoltaic panel recycling a much more manageable problem than, for example, recovering and recycling Cd from Ni-Cd batteries [18]. Programs to collect used batteries have limited effectiveness, so it is difficult to recycle more than a modest fraction of spent batteries — the rest end up in landfills.

In addition to the relative ease of collecting modules from solar facilities, the simple construction of CdTe photovoltaic modules and limited number of components make it relatively straightforward to separate the materials for recycling. Industrial crushing and classification schemes separate the glass and metallic components so they can be re-manufactured. During recycling, the CdTe film is also extracted from the panel's glass substrate with chemical solvents (concentrated sulfuric acid and hydrogen peroxide) [35].

With current technology, over 90 percent of a CdTe photovoltaic power system is recyclable; that is roughly twice what is recoverable from consumer electronics such as laptops and desktop computers [36]. Recycling of decommissioned CdTe photovoltaic modules is now available on an industrial scale at several sites around the world, including in the United States. A proactive recycling plan for the modules can help ensure CdTe is available for use in future thin film photovoltaic module production. Recycling is important for all photovoltaic technologies to recover energy intensive, valuable, and environmentally sensitive materials.

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