CC-SC Website Topic/Tab	CC-SC Concern/claim	sPower's response	Notes/Comments
Home	Thousands of acres are to be cleared if the project is approved.	All current timber management and harvesting practices are being conducted by the current property owner.	It is worth noting that these stands are on a 20-year harvest rotation, which means the current clear cut conditions are nothing new or out of the ordinary, and future clear cuts would be anticipated if the property stays in current land use.
	Taxes will go up	This is incorrect.	The s Power proposed site will actually generate more tax revenue to include approaximately $10 million vs. $700,000 as compared to current tax rate
	Consumer price for electricity will go up	The project is selling into the PJM wholesale market, and has no impact on the cost of electricity for a VA rate payer. The VA electricity rate are exclusively determined by the SCC.	The SCC has determined our project will have no impact on consumer rates
	Property values will go down	There is no evidence for this, nor is there a clear consensus on the effect of solar farms on neighboring property values, positive or negative.	Values of real estate has more to do with location and market. The Fawn Lake community will soo no adverse impact to property values due to this project. To conclude otherwise is mere speculation.
	Water pressure is going to go down and access to well water will be diminished.	**This is untrue.** sPower has made the commitment to utilize only municipal water, and will consider groundwater only during the emergency scenario of a municipal water system failure (which would be capped at 10 days of use). sPower has also committed to a private/public partnership to enhance the municipal water system with the county.	sPower has agreed to pay for municipal water as opposed to on-site wells for groundwater. Furthermore, when approached by Spotsylvania County regarding water utility improvements which had been contemplated for years, but lacked sufficient county funding, sPower agreed to a public-private partnership to cost-share the improvements. sPower feels this has been addressed and clarified multiple times.
	Toxic runoff and contamination of our water supply	**Cadmium Telluride is not the same thing as free Cadmium.** Cadmium Telluride (CdTe) is an extremely stable, nontoxic compound. sPower has provided thorough evidence and research to County Staff demonstrating the chemical stability of CdTe. This research has demonstrated Cadmium Telluride is non-toxic, and passes EPA standards for environmental and human health and safety.	Refer to the CdTe panel safety and integrity Executive Summary previously provided to County Staff (Exhibit 1)
Massive Scale	The 5th largest in the United States. All of the four larger U.S. solar power plants (above 500 MW) are located in remote desert areas of California and Nevada. Furthermore, all 14 solar power plants in the U.S. that are 250 MW or greater are in California, Nevada and Arizona.	As the price for solar has dropped, solar energy has become cost-effective in areas, such as Virginia, that previously were not cost-competitive and solar facilities can operate in new environments outside of deserts.	Renwables are becoming a more in demand energy supply and technology offtakers are driving much of this demand
	The "solar heat island effect" could significantly impact the local climate of the site and surrounding areas. This risk is scale dependent, and much more research is needed to understand and mitigate the impacts in this region, near residential neighborhoods, farms, schools. Current studies of this effect are based on 1 MW facilities. One megawatt. The Spotsylvania plant ... is 500 MW.	While it is true that temperatures within the solar field may be a few degrees higher than the surrounding area, studies have found that the temperature difference dissipates quickly in just a few feet above and away from the solar site, especially with vegetation and trees, and berms. The data also demonstrates the solar fields cool-off completely at night, making heat-island effect unlikely. The research also indicates that scale should have no effect on these findings as the solar fields increase in size.	Refer to the Heat Island Effect Executive Summary previously provided to County Staff (Exhibit2)
Aquifer Damage	sPower needs more than 200 million gallons of water during 18 months of construction. (The company originally estimated more than 300 million gallons. After Concerned Citizens first flagged this as a danger to the aquifer, sPower reduced the estimate.) In any event, sPower plans to withdraw the water they need from new large wells. The state will not impose restrictions on water usage. Any restrictions must be imposed by the county via the Special Use Permit conditions.	After listening to community concerns, sPower has redesigned the grading and developments plans for the project that were initially proposed, which consequently reduced the anticipated water need to less than 100,000 gallons per day. It is worth noting this new grading plan comes at a considerable economic cost. sPower has made the commitment to utilize only municipal water, and will consider groundwater only during the emergency scenario of a municipal water system failure (which would be capped at 10 days of use). sPower has also committed to a private/public partnership to enhance the municipal water system with the county.	Power has a greed to public-private partnership to cost-share the improvements.
	In addition, sPower estimates that 8 million gallons per year is needed during operation. The water will be used for landscaping and panel washing. Peak loads during panel washing could be millions of gallons in a few days.	**This is inaccurate.** Water usage will be minimal during the operations phase of the project. Spotsylvania County receives more than enough annual precipitation to render panel washing unnecessary.	
	Excessive extraction of water from new large capacity wells could lower groundwater levels and irreversibly damage the aquifer.	**This is no longer an issue.** sPower has made the commitment to utilize only municipal water, and will consider groundwater only during the emergency scenario of a municipal water system failure (which would be capped at 10 days of use).	
	A recent geology study by GEO SEER concludes: "The local aquifer is not robust enough to sustain industrial taps in quantity to supply water to a solar power site of the proposed magnitude... The current plan, as provided by sPower, would lead to the collapse of the area aquifer."	**This is no longer an issue.** sPower has made the commitment to utilize only municipal water.	
	There are thousands of households that depend on well water in Spotsylvania County. Many of these residents report problems with their wells during periods of drought. Further stress on the aquifer could exacerbate the problems, requiring Spotsylvania County to spend millions of dollars to supply drinking water.	**This is no longer an issue.** sPower has made the commitment to utilize only municipal water.	
	This is no longer an issue. sPower has made the commitment to utilize only municipal water, and will consider groundwater only during the emergency scenario of a municipal water system failure (which would be capped at 10 days of use).	**This is no longer an issue.** sPower has made the commitment to utilize only municipal water.	

Toxic Materials	The 1.8 million photovoltaic solar panels will contain approximately 100,000 pounds of Cadmium, which is a highly toxic carcinogen.	Cadmium Telluride (CdTe) is not the same as raw Cadmium. Cadmium Telluride is incredible stable and passes EPA standards for environmental health and safety.	Refer to the CdTe panel safety and integrity Executive Summary previously provided to County Staff (Exhibit 1). Also, although the issue is moot given the stability of CdTe, CCSC's calculations seems to be inaccurate: Each CdTe panel only contains 7g of CdTe (which is, again inert). sPower is only proposing to put 440,000 CdTe panels on site. 7g x 440,000= 3,080,000g =6,790 lbs. (inert)
	sPower denies any health risk from the Cadmium in the panels, but scientific studies show that leaching of Cadmium from broken panels occurs over time. Scientific studies show very high quantities of Cadmium can leach out in a few months in acidic conditions. Our soil and Virginia clay are acidic, so rapid and thorough cleanup of any damaged Cadmium-containing panels is critical.	The one (1) study the citizens are referring to is "Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions" by Ramos-Ruiz et al. It is worth noting this particular study <u>does not simulate real-world conditions</u> for several reasons, and the citizens neglect to mention all of the study's findings: in particular that the results from the EPA TCLP analysis were negligible.	Please note above reference
	Toxic chemicals such as herbicides and pesticides should be carefully controlled and only applied by certified professionals.	sPower agrees and will follow all applicable permits for the application of these substances.	
	Cleaning agents may also be toxic to the environment. sPower indicates that cleaning agents will not be used, as such would void their warranties on solar panels.	This is correct, and as mentioned previously, there is no anticipated need to clean the panels due to the high amount of precipitation in the county.	
	Severe weather such as a tornado, hurricane, or derecho -- now somewhat common occurrences in central Virginia, and typically accompanied by heavy rains -- could cause widespread destruction of solar panels and subsequent leaching of Cadmium, followed by toxic and carcinogenic runoff into Spotsylvania's water supply.	These panels are designed to withstand sever weather events. In the instance a panel is damaged, our real-time monitoring systems will allow us to identify and replace damaged panels instantly.	Refer to the CdTe panel safety and integrity Executive Summary previously provided to County Staff (Exhibit 1)
	sPower has not produced any scientific reports that show what happens to the Cadmium contained in solar panels during such a catastrophic event. We know that tornados and hurricanes have hit large solar plants - where are the scientific reports of what was found, and how it was cleaned up?	We have provided a whole Executive Summary containing multiple studies on the topic.	Refer to the CdTe panel safety and integrity Executive Summary previously provided to County Staff (Exhibit 1)
	Consider the possibility of a lightning strike and fire. The site will have hundreds of thousands of steel piles driven in the ground attached to metal frames - magnets for lightning. This in an area the size of Fredericksburg with a few gravel roads, no fire hydrants, no fire station. How will our emergency responders be able to handle it?	sPower has coordinated with county FREM and discussed fire safety and emergency response access, which is covered in our Emergency Response Plans, which were provided to County Staff.	Refer to the Emergency Response Plans during both Construction and Operations (Exhibits 3 and 4)
Erosion and Runoff	Most of the 6,350 forested acres have been logged and will be cleared. Significant soil regrading is anticipated to provide vast flat fields for the solar panels.	sPower has made significant and costly modifications to our grading plan, reducing the amount of grading and earthwork than what was previously proposed. Also, the project will be phased with only 400 acres open and active at any one time in any one watershed.	
	Specific plans are needed to prevent severe muddy runoff problems, such as recently encountered in Essex County due to construction of a 200 acre solar farm -- after only 1/2" of rain	sPower has committed to several Stormwater and Erosion control measure that go above and beyond what is required by county and state regulations, including but not limited to: sediment basins that are over-sized for their respective drainage areas, an accelerated sediment removal regime (cleaning the basins twice as frequently as required), diversion ditches on top of proposed slope to further divert and slow runoff, and stormwater conveyance channels and ditches at full design (a level of design effort reserved for the site development plan stage). Spotsylvania County has reviewed and approved these designs.	
	The soil in our area is not hydric, so rainwater will not percolate into the soil, but instead will rapidly runoff the Virginia clay which will be exposed by regrading the site. As noted on our Toxic Materials page, if the runoff contains such materials, big problems might arise such as water contamination, killing of fish and the endangered dwarf wedgemussel, etc.	See the above mentioned additional/excessive runoff control measures. Also, as previously stated above, runoff containing CdTe is not a concern.	
	Several environmentally important streams run through the property. Robertson Run and McCracken Creek are designated Threatened and Endangered Species Waters. Runoff would flow into the Po, Mattaponi, and York Rivers, and then into the Chesapeake Bay. In addition, Plentiful Creek has a “moderate” environmental significance rating. These waterways and wetlands must be protected to avoid environmental harm, which could flow all the way into the Chesapeake.	All streams and wetlands have 50' designated Resource Protection Area (RPA) buffers surrounding them, as well as the above mentioned additional/excessive runoff control measures. Besides coordinating with County staff, sPower has coordinated and consulted with all relevant State and Federal agencies and will follow all applicable permits and regulations to ensure natural resource protections.	
	The reason that sPower must buy 6350 acres to install 3500 acres of solar panels is because the rest of the site is either wetlands, or is too steep to install panels. This site has a lot of streams and wetlands. It is not the typical topography for a solar power plant of this size. The environmental risks here are much greater.	All streams and wetlands have 100' designated Resource Protection Area (RPA) buffers surrounding them, as well as the above mentioned additional/excessive runoff control measures. Besides coordinating with County staff, sPower has coordinated and consulted with all relevant State and Federal agencies and will follow all applicable permits and regulations to ensure natural resource protections.	

	The County has stated that site preparation must be done in stages, limited to 400 acres at a time. Soil stabilization and stormwater management measures must be in place before any additional land is disturbed. Concerned Citizens supports a staged approach. We recommend that rather than building the entire site at once, that the project be phased in over a period of five or more years, allowing the county board and staff adequate time to review each phase and address development concerns, and requiring sPower to address and mitigate them before further expanding the site. This step-wise approach is prudent given the unprecedented size of the proposed facility.	The project will be completed in Phases and land disturbance will be limited to 400 acres per watershed. All land disturbance plans are permitted and approved through the county and the state.
	Strict controls are needed covering selection and application of chemicals used during construction (e.g. herbicides to clear vegetation) and operation (e.g. fertilizers, herbicides, pesticides, cleaning agents).	sPower agrees and will follow all applicable permits for the application of these substances.
	sPower has indicated that they will not use biosolids to condition soil. (Biosolids, if used, could pollute the groundwater and drinking water drawn from the rivers downstream.)	This is correct.
Restoration Costs	sPower is establishing Pleinmont Solar, LLC and four other LLCs for the construction and operation of this facility.	This is correct and each one of these LLCs are wholly owned subsidiaries of sPower.
	sPower's initial estimate for the decommissioning bond was a mere $1.2 million. They recently increased it to $5.4 million after taking generous credits for the value of recycled materials. Our estimates indicate that the bond should be about $100,000 per MW, or about $50 million	sPower and our construction partners' successful track record of developing several gigawatts of solar energy, and years of industry experience allows us to be comfortable in our estimates. Additionally, the solar panel have value beyond the life of the project and would be reused/redeployed in the event of a decommissioning.
	Costs for decommissioning and removing all of the equipment, and remediating any contamination must be guaranteed not only from the subsidiary LLCs, but also sPower corporation, the actual operator of the facility.	The Decommissioning Bond is guaranteed by third party bonding and given the value of the assets for this project and financing for the same, we are confident the project will be viable for the long term as an ongoing operational generation facility.
	If the site is abandoned, then the County and State -- and we the taxpayers -- will have a large toxic waste site to clean up. Without an adequate bond, we also will not have the money for the cleanup	The site will not be abandoned; sPower has 15-year offtaker contracts with AAA+ credit rated entities. The site is not toxic. Any bond posted will be more than adequate and reviewed on a 2-year basis.
	Further, the restoration of the site to its original condition is likely not achievable, or will be many years after the decommissioning of the power plant.	If in 35 years sPower decides to decommission the site, rather than renew or extend operations, and the county wishes the property to return to it's original land use, reversion back to timberland will take the same amount of time as after a clear-cut under current use.
Preserve History	The proposed power plant must not detract from that aspect and the character of our community.	sPower has conducted an archeological survey of the proposed project property and submitted it to the Virginia DHR for review. Concurrence of no adverse impact was received 9/10/18
Protect Viewsheds	However, sPower's site plan does not support that claim. They plan to install solar panels as close as 50 ft from their property line, and not provide any sight or sound barriers around most of the perimeter	**This is incorrect.** The project has designs for setbacks of 150-400 feet from the property line, vegetated berms ranging from 6-8 ft, and 50 ft vegetated visual buffers around the property. sPower has also conducted noise impact studies in order to mitigate construction noise. All visual simulations and designs and noise studies have been submitted to County Staff.
Defend Taxpayers	There are many ways that this privately owned commercial enterprise -- a heavily subsidized speculative investment propped up by price guarantees -- might adversely affect taxpayers: through increased electricity rates, potential bankruptcies of the "limited liability" corporations established to build and operate it once the current huge federal and state subsidies expire, and potential loss in property values and thus the principal tax basis of the county. And eventually, the cost to clean up the site.	1. Electricity rates will not be affected. 2. sPower will be posting a decommissioning bond to cover removal of the project in the unlikely event anything goes South. 3. There is no clear consensus or indication of the effect on property values, positive or negative.

Exhibit 1
Cadmium Telluride Panel Executive Summary

Cadmium Telluride Panel Integrity and Safety
Executive Summary

- It is important to distinguish that Cadmium Telluride (CdTe) is not the same as free Cadmium.
- CdTe is a very stable compound that is non-volatile and non-soluble in water. The vapor pressure of CdTe at ambient conditions is zero. Therefore, it is impossible for any vapors or dust to be generated when using PV modules. CdTe has a melting point of 1041°C (1905 °F) and boiling point 1050^{o}C (1922°F).
- The panel's thin layer of CdTe is encapsulated between two sheets of glass and sealed with an industrial laminate, which further limits the potential for release into the environment in the event of breakage.
- Panel breakage is rare and occurs only in approximately 1% of modules over 25 years, or 0.04% per year. More than one-third of breakages occur during shipping and installation; therefore, the broken modules are removed prior to plant operation (First Solar).
- Panels are subject to a battery of reliability tests simulated for violent weather (heavy wind, rain, hail) to ensure integrity without damage in the field (https://www.youtube.com/watch?v=rtxgeCH31EI)
- Using the Toxicity Characteristic Leaching Procedure (TCLP), worst-case scenario modeling of total release (which is, again, very implausible) of CdTe (which is, again, very stable) from broken panels, estimated Cd concentrations in soil, groundwater, and air to be below health screening levels, background levels, and common levels in agricultural fertilizers. (Sinha et al. 2012)
- It's worth noting that the TCLP used in these analyses is very conservative, as it assumes the panels break into pieces and fall directly to the ground, which is not the case: field breakages mainly consist of various types of stress and impact fractures in which panels remain largely intact with a number of glass fractures or cracks, rather than break into pieces. (Sinha and Wade 2015)
- Multiple sources report that CdTe PV end-of-life or broken panels pass Federal (TCLP-RCRA) leaching criteria for non-hazardous waste. Therefore, panels could be disposed of in landfills (NC State 2017).
- Even in the case of a fire, research shows that less than 0.1% of the cadmium is released when a CdTe panel is exposed to fire. The fire melts the glass and encapsulates over 99.9% of the cadmium in the molten glass. (Fthenakis et al. 2005)

Regarding the bigger picture:

- CdTe panels do not result in more Cadmium in the environment.
- Substantial quantities of Cadmium are generated as a by-product of zinc production for steel products, regardless of how much Cadmium is used in PV. Encapsulating and stabilizing cadmium as CdTe in PV panels presents a safer option than its current uses, and is much more preferred to disposing it. (Fthenakis and Zweibel 2003)

- Phosphate fertilizers represent the major source of cadmium in agricultural soils and the combustion of fossil fuels represents the primary source of Cd emissions to air. (Six and Smolders 2014)
- Whenever CdTe PV replaces coal in power generation it lowers the associated Cd emissions to air by 100–360 times. (Raugei and Fthenakis 2010)

Citations:

First Solar "CdTe PV FAQ", 2017

North Carolina State University Clean Energy Technology Center, "Health and Safety Impacts of Solar Photovoltaics". 2017

Fthenakis and Zweibel, "CdTe PV: Real and Perceived EHS Risks". Presented at the National Center for Photovoltaics and Solar Program Review Meeting Denver, Colorado March 24-26, 2003

Fthenakis et al., "Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires," *Progress in Photovoltaics: Research and Applications,* vol. 13, no. 8, pp. 713-723, 2005.

Raugei and Fthenakis, "Cadmium Flows and Emissions from CdTe PV: Future Expectations," *Energy Policy,* vol. 38, no. 9, pp. 5223-5228, 2010. (First Solar FAQ Document)

Sinha et al., "Fate and Transport Evaluation of Potential Leaching Risks from Cadmium Telluride Photovoltaics," *Environmental Toxicology and Chemistry,* 2012.

Sinha, Parikhit & Wade, Andreas. (2015). Assessment of Leaching Tests for Evaluating Potential Environmental Impacts of PV Module Field Breakage. IEEE Journal of Photovoltaics. 5. 1-5. 10.1109/JPHOTOV.2015.2479459.

Six and Smolders, "Future trends in soil cadmium concentration under current cadmium fluxes to European agricultural soils," *Science of The Total Environment,* vol. 485–486, p. 319–328, 2014. (First Solar FAQ Document)

First Solar Panel Quality Assurance Video

YouTube: "First Solar Module Reliability"
https://www.youtube.com/watch?v=rtxgeCH31EI

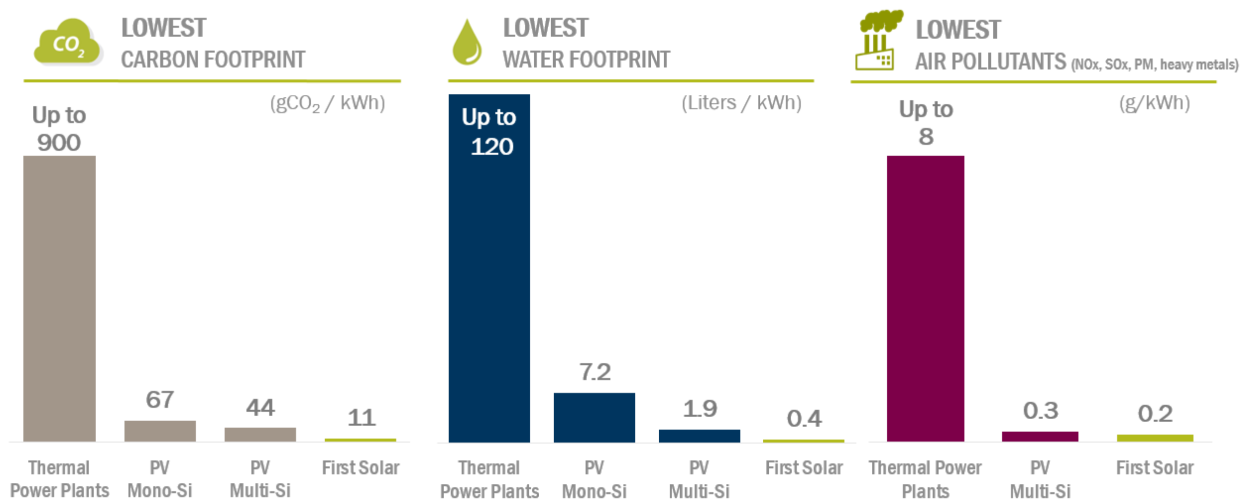
Appendix

Cited Materials

CdTe PV FAQ

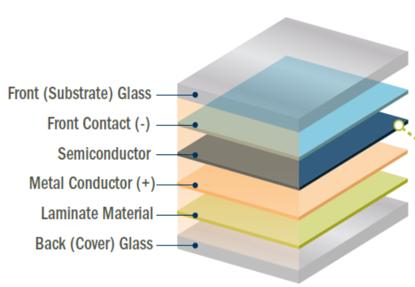
What are the environmental benefits of First Solar's thin film PV technology?

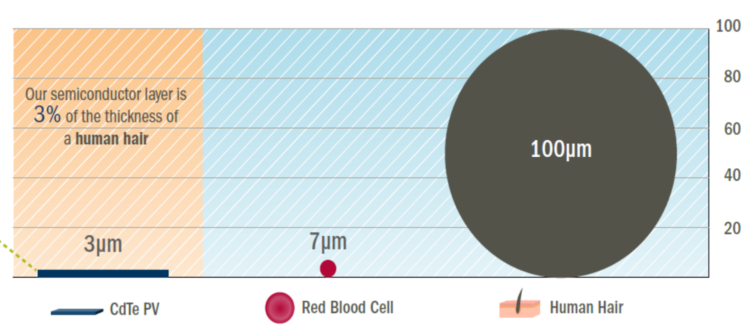
First Solar's advanced thin film PV solutions are the industry's leading eco-efficient technology due to their superior energy yield, competitive cost and smallest life cycle environmental impacts. [1] By using less grid electricity during manufacturing, First Solar thin film modules have the smallest carbon footprint and lowest life cycle water use and air pollutants of any PV technology on the market. [2] [3] [4] [5] [6] According to a study by UNEP, CdTe PV has the lowest life cycle human health and ecological impacts of all PV technologies per kWh of electricity produced. [7]



What is cadmium telluride (CdTe)?

CdTe is a semiconductor material used in First Solar PV modules that is ideal for absorbing and converting sunlight into electricity. Because CdTe is almost perfectly matched to the solar spectrum, First Solar modules require 98-99% less semiconductor material than conventional crystalline silicon modules. The semiconductor layer in First Solar modules is a few microns thick, equivalent to 3% the thickness of a human hair or less than half the thickness of a red blood cell.



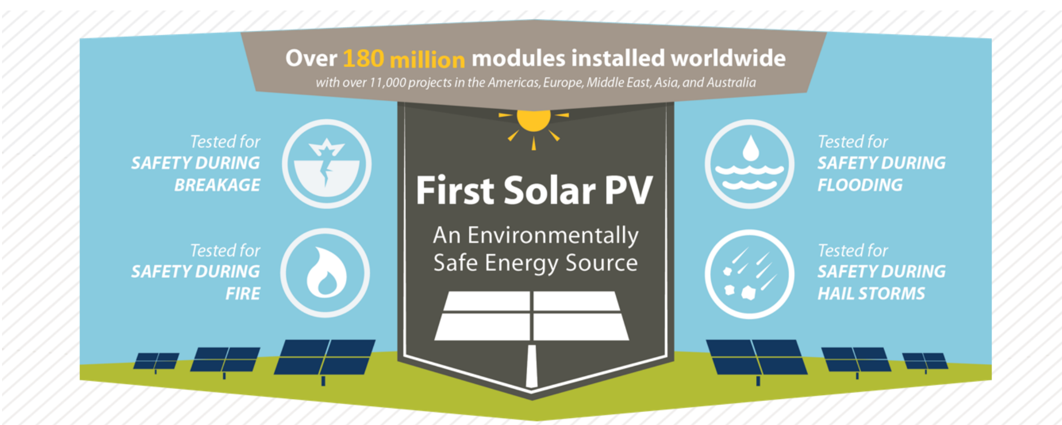


Is CdTe the same as cadmium?

No, third-party research studies have shown that CdTe differs from cadmium (Cd) due to its extremely high chemical and thermal stability. [8] CdTe is a stable compound that is insoluble in water, has a melting point (1041°C) and boiling point (1050^{0}C), and a low evaporation rate. In addition, First Solar's thin film semiconductor is encapsulated between two sheets of glass and sealed with an industrial laminate, which further limits the potential for release into the environment in the event of fire or breakage.

Does CdTe PV technology pose a risk to human health or the environment?

No. More than 40 researchers from leading international institutions have confirmed the environmental benefits and safety of First Solar's thin film PV technology over its entire life cycle; during normal operation, exceptional accidents such as fire or module breakage, and through end-of-life recycling and disposal: http://www.firstsolar.com/Resources/Sustainability-Documents?ty=Peer+Reviews&re=&ln=%20. First Solar thin film modules have been tested for safety during breakage, fire, flooding and hail storms and meet rigorous performance testing standards, demonstrating their durability and reliability in real-world environments. With over 17,000 MW deployed worldwide, First Solar thin film modules have a proven record of safe and reliable performance.



"CdTe modules do not represent any risk for human health nor for the environment, during normal operating conditions and in the exceptional case of fire or breakage." [9]

- National Renewable Energy Centre (CENER)

"Research demonstrates that [CdTe PV modules] pose negligible toxicity risk to public health and safety while significantly reducing the public's exposure to cadmium by reducing coal emissions." [10]

–North Carolina State University

"…replacing coal generation with [CdTe] PV will prevent Cd emissions in addition to preventing large quantities of CO2, SO2, NOx, and particulate emissions." [11]

- National Renewable Energy Laboratory and Brookhaven National Laboratory

Are First Solar modules certified to EHS, quality and durability standards?

All First Solar manufacturing plants are certified to ISO 14001 for Environmental Management, ISO 9001 for Quality, and OHSAS 18001 for Occupational Health and Safety. First Solar modules are certified to regional standards including UL for North America, CEC for Australia, Golden Sun for China, MCS for the U.K. and JET for Japan. First Solar PV modules also meet rigorous performance testing standards, demonstrating their durability and reliability in real-world environments.

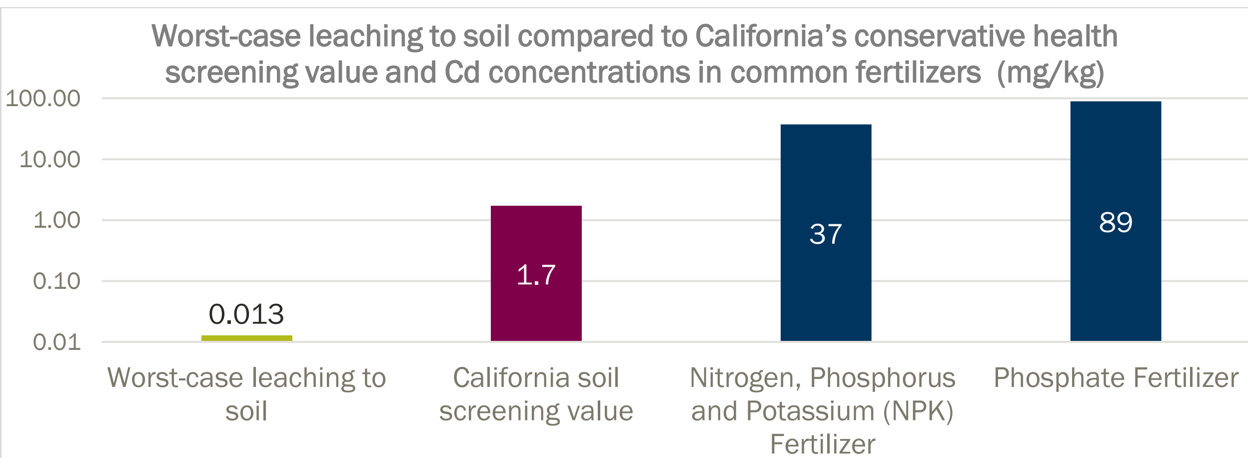
Test	Description	Results
IEC 61646/ IEC 61730 Certification	Basic industry market entry certifications	PASS *1500V certification level*
UL 1703	PV module electrical safety	PASS
Fire rating	Flammability testing	Class A Spread of Flame Class B Burning Brand
Thresher Test	Multiplies basic IEC 61730/61646 test cycles and durations 2X to 4X	PASS *<5% Power Output drop*
Long-Term Sequential Test	6-month accelerated protocol to evaluate long-term harsh climate durability	PASS *1st thin film module, and one of only 5 modules in the*
Atlas 25+ Certification	12-month weathering-intensive certification through projected 25+ year harsh climate field lifetimes	PASS *One of only 4 modules in the world to pass.*
IEC 62804 PID-Resistant Certification	Demonstrates high resistance to potential induced degradation at extreme ± 1500V voltages at most extreme 192hr 85C/85% RH test levels, enabling confident floating and grounded applications	PASS *1500V*
IEC 60068 Certification Desert Sand Resistance	Demonstrates minimal power loss and package integrity resistant to wind-blown particulates	PASS
Fraunhofer PV Durability Initiative	Durability benchmarking program rates modules according to their likelihood of performing reliably over their expected service life based on accelerated stress testing and long-term outdoor exposure	PASS *Best-in-class long term durability*
VDE Quality Tested	Quality certification for entire PV power plant enhances performance, ensures electrical and mechanical safety of the system and provides independent verification to investors, lenders and insurance companies.	PASS 1st PV company to achieve certification

What could happen if modules break?

Module breakage is rare and occurs only in approximately 1% of modules over 25 years or 0.04% per year. More than one-third of breakages occur during shipping and installation, therefore the broken modules are removed prior to plant operation. During operation, most breakages consist of impact fractures in which the module is still bound together by the industrial laminate.

Even in a worst-case leaching scenario, which assumes all the CdTe from broken modules were to leach as cadmium into the rainfall, Cd concentrations in soil, air, and groundwater are still below conservative human health screening levels in California. [12]

Modelled results for worst-case leaching to soil are up to 7,000 times lower than cadmium concentrations in common fertilizers.



What could happen in the event of a fire?

Independent analysis indicates potential Cd emissions from CdTe PV modules involved in a fire would be negligible as the majority of CdTe would remain encapsulated in glass. Heating experiments simulating residential fires showed that 99.96% of the Cd content of CdTe PV modules would be encapsulated in molten glass under the high temperatures of a building fire (800 to 1100˚C). [13] For ground-mount systems, the short-lived maximum fire temperatures (1000°C) are below the melting point of CdTe (1041°C), limiting release. [14] Even in a worst-case scenario that assumes a maximum Cd content (66.4 g/m^2) more than four times the amount of CdTe contained in First Solar modules, a large fire area, and the shortest distance from the emission site, the calculated Cd emission concentration is still below conservative air pollution exposure limits for the public and emergency responders. [15]

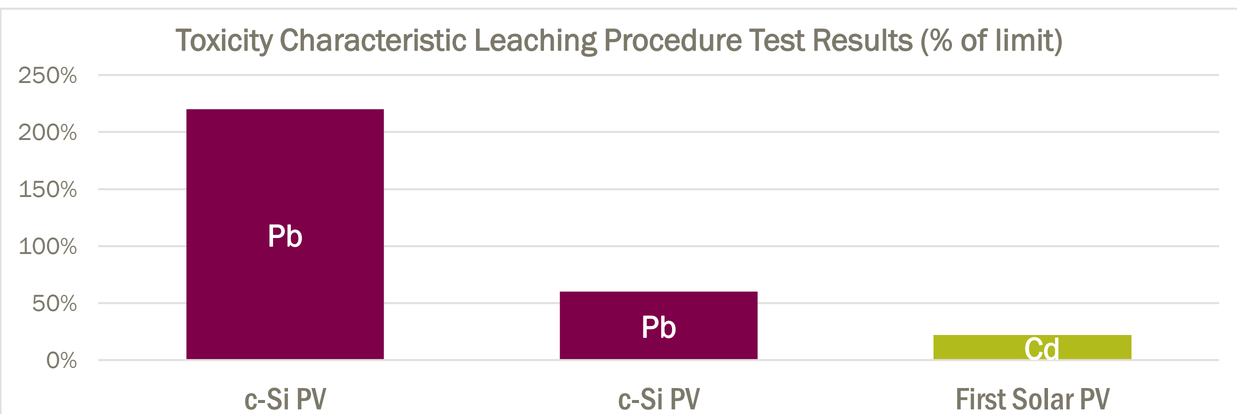
For perspective, potential accidental emissions occurring during fires are up to three orders of magnitude lower than routine emissions from coal and oil power plants. [16]

Does CdTe PV lead to an increase of cadmium in the environment?

No. Cadmium is generated as an unavoidable by-product of zinc production for steel products, regardless of its use in PV. Increased steel demand for building, construction and automobiles is expected to lead to a potential oversupply of cadmium. [17] When combined with tellurium, cadmium is converted into a stable compound, which is used to generate clean electricity for 25+ years. Cadmium exposure to the general population primarily occurs via smoking, followed by ingestion of Cd-containing food. Phosphate fertilizers represent the major source of cadmium in agricultural soils and the combustion of fossil fuels represents the primary source of Cd emissions to air. [18] [19] Whenever CdTe PV replaces coal in power generation it lowers the associated Cd emissions to air by 100–360 times. [20]

Does CdTe PV technology have unique end-of-life management requirements?

No. Responsible end-of-life management is important to the whole PV sector in order to maximize resource recovery and manage environmentally sensitive materials which are common in the industry. Both CdTe and crystalline silicon PV modules contain comparable quantities of heavy metals. Leaching tests results found that crystalline silicon PV modules released a range of 3-11mg/L of lead (Pb), which corresponds to 60%-220% of the federal U.S. waste characterization test (TCLP) limit. [21] Potential environmental impacts from end-of-life disposal of crystalline silicon PV modules are therefore comparable to or greater than that of CdTe PV.



Can First Solar modules and PV power plants be recycled at end-of-life?

Yes. Over 90% of a First Solar PV power plant is recyclable. First Solar has a long-standing leadership position in PV recycling and provides global PV module recycling services that enable PV power plant owners to meet their decommissioning and end-of-life (EOL) requirements simply, cost effectively and responsibly. First Solar's high-value recycling process recovers approximately 90% of the glass for reuse in new glass products and over 90% of the semiconductor material for reuse in new modules. The remainder of the recycled module scrap (approximately 5 to 10%) which cannot be used in secondary raw materials is handled using other responsible waste treatment and disposal techniques. Due to the shredding, crushing and heating typically involved in recycling processes, material losses are inevitable and the recovery ratio is always less than 100%. [22]

References

[1] Seitz et al., "Eco-Efficiency Analysis of Photovoltaic Modules," Bavarian State Ministry of Environment and Health, 2013.

[2] M. de Wild-Scholten, "Energy Payback Time and Carbon Footprint of Commercial Photovoltaic Systems," *Solar Energy Materials & Solar Cells,* vol. 119, pp. 296-305, 2013.

[3] Fthenakis and Kim, "Life Cycle Uses of Water in U.S. Electricity Generation," *Renewable and Sustainable Energy Reviews,* vol. 14, p. 2039–2048, 2010.

[4] Sinha et al., " Life Cycle Water Usage in CdTe Photovoltaics," *IEEE Journal of Photovoltaics,* 2012.

[5] Stolz and Frischknecht, "Water Footprint of Photovoltaic Electricity based on Regionalised Life Cycle Inventories," in *33rd EU PVSEC*, Amsterdam, 2017.

[6] Sinha et al., "Total Cost Electricity Pricing of Photovoltaics," in *28th EU PVSEC Conference*, Paris, 2013.

[7] United Nations Environment Programme (UNEP), "Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production," Report of the International Resource Panel, 2016.

[8] S. Kaczmar, "Evaluating the Read-Across Approach on CdTe Toxicity for CdTe Photovoltaics," in *SETAC North America 32nd Annual Meeting*, Boston, 2011.

[9] CENER and Fundacion Chile, "First Solar CdTe Photovoltaic Technology: Environmental, Health and Safety Assessment," 2013.

[10] North Carolina Clean Energy Technology Center, "Health and Safety Impacts of Solar Photovoltaics," North Caroline State University, 2017.

[11] Fthenakis and Zweibel, "CdTe Photovoltaics: Real and Perceived EHS Risks," in *Paper presented at National Center for Photovoltaics and Solar Program*, Brookhaven National Laboratory (BNL) and National Renewable Energy Laboratory (NREL), 2003.

[12] Sinha et al. , "Fate and Transport Evaluation of Potential Leaching Risks from Cadmium Telluride Photovoltaics," *Environmental Toxicology and Chemistry,* 2012.

[13] Fthenakis et al. , "Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires," *Progress in Photovoltaics: Research and Applications,* vol. 13, no. 8, pp. 713-723, 2005.

[14] Sinha, Balas and Krueger, "Fate and transport evaluation of potential leaching and fire risks from CdTe PV," in *37th IEEE Photovoltaic Specialists Conference*, Seattle, WA, 2011.

[15] Beckmann and Mennenga, "Calculation of emissions when there is a fire in a photovoltaic system made of cadmium telluride modules," Bavarian Environmental Agency, Augsberg, Germany, 2011. (Available at: www.lfu.bayern.de/luft/doc/pvbraende.pdf).

[16] Fthenakis et al., "Emissions from Photovoltaic Life Cycles," *Environmental Science & Technology,* vol. 42, no. 6, p. 2168–2174, 2008.

[17] Matsuno et al., "Dynamic Modeling of cadmium substance flow with zinc and steel demand in Japan," *Resources Conservation and Recycling,* vol. 61, pp. 83-90, 2012.

[18] Six and Smolders, "Future trends in soil cadmium concentration under current cadmium fluxes to European agricultural soils," *Science of The Total Environment,* vol. 485–486, p. 319–328, 2014.

[19] F. Van Assche, "Trends in Cd emissions and Cd in the environment," in *9th International Cadmium Conference*, Lisbon, 2016.

[20] Raugei and Fthenakis, "Cadmium Flows and Emissions from CdTe PV: Future Expectations,," *Energy Policy,* vol. 38, no. 9, pp. 5223-5228, 2010.

[21] Sinha and Wade, "Assessment of leaching tests for evaluating potential environmental impacts of PV module field breakage," *IEEE Journal of Photovoltaics,* vol. 5, no. 6, pp. 1710 - 1714, 2015.

[22] McKinney, Schoch, and Yonavjak, "Mineral Resources, Environmental Science Systems and Solutions," *Jones & Bartlett Learning,* 2013.

Health and Safety Impacts of Solar Photovoltaics

The increasing presence of utility-scale solar photovoltaic (PV) systems (sometimes referred to as solar farms) is a rather new development in North Carolina's landscape. Due to the new and unknown nature of this technology, it is natural for communities near such developments to be concerned about health and safety impacts. Unfortunately, the quick emergence of utility-scale solar has cultivated fertile grounds for myths and half-truths about the health impacts of this technology, which can lead to unnecessary fear and conflict.

Photovoltaic (PV) technologies and solar inverters are not known to pose any significant health dangers to their neighbors. The most important dangers posed are increased highway traffic during the relative short construction period and dangers posed to trespassers of contact with high voltage equipment. This latter risk is mitigated by signage and the security measures that industry uses to deter trespassing. As will be discussed in more detail below, risks of site contamination are much less than for most other industrial uses because PV technologies employ few toxic chemicals and those used are used in very small quantities. Due to the reduction in the pollution from fossil-fuel-fired electric generators, the overall impact of solar development on human health is overwhelmingly positive. This pollution reduction results from a partial replacement of fossil-fuel fired generation by emission-free PV-generated electricity, which reduces harmful sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$). Analysis from the National Renewable Energy Laboratory and the Lawrence Berkeley National Laboratory, both affiliates of the U.S. Department of Energy, estimates the health-related air quality benefits to the southeast region from solar PV generators to be worth 8.0 ¢ per kilowatt-hour of solar generation.[1] This is in addition to the value of the electricity and suggests that the air quality benefits of solar are worth more than the electricity itself.

Even though we have only recently seen large-scale installation of PV technologies, the technology and its potential impacts have been studied since the 1950s. A combination of this solar-specific research and general scientific research has led to the scientific community having a good understanding of the science behind potential health and safety impacts of solar energy. This paper utilizes the latest scientific literature and knowledge of solar practices in N.C. to address the health and safety risks associated with solar PV technology. These risks are extremely small, far less than those associated with common activities such as driving a car, and vastly outweighed by health benefits of the generation of clean electricity.

This paper addresses the potential health and safety impacts of solar PV development in North Carolina, organized into the following four categories:

(1) Hazardous Materials
(2) Electromagnetic Fields (EMF)
(3) Electric Shock and Arc Flash
(4) Fire Safety

1. Hazardous Materials

One of the more common concerns towards solar is that the panels (referred to as "modules" in the solar industry) consist of toxic materials that endanger public health. However, as shown in this section, solar energy systems may contain small amounts of toxic materials, but these materials do not endanger public health. To understand potential toxic hazards coming from a solar project, one must understand system installation, materials used, the panel end-of-life protocols, and system operation. This section will examine these aspects of a solar farm and the potential for toxicity impacts in the following subsections:

1.1 Project Installation/Construction

The system installation, or construction, process does not require toxic chemicals or processes. The site is mechanically cleared of large vegetation, fences are constructed, and the land is surveyed to layout exact installation locations. Trenches for underground wiring are dug and support posts are driven into the ground. The solar panels are bolted to steel and aluminum support structures and wired together. Inverter pads are installed, and an inverter and transformer are installed on each pad. Once everything is connected, the system is tested, and only then turned on.

Figure 1: Utility-scale solar facility (5 MW_{AC}) located in Catawba County. Source: Strata Solar

1.2 System Components

1.2.1 Solar Panels: Construction and Durability

Solar PV panels typically consist of glass, polymer, aluminum, copper, and semiconductor materials that can be recovered and recycled at the end of their useful life.[2] Today there are two PV technologies used in PV panels at utility-scale solar facilities, silicon, and thin film. As of 2016, all thin film used in North Carolina solar facilities are cadmium telluride (CdTe) panels from the US manufacturer First Solar, but there are other thin film PV panels available on the market, such as Solar Frontier's CIGS panels. Crystalline silicon technology consists of silicon wafers which are made into cells and assembled into panels, thin film technologies consist of thin layers of semiconductor material deposited onto glass, polymer or metal substrates. While there are differences in the components and manufacturing processes of these two types of solar technologies, many aspects of their PV panel construction are very similar. Specifics about each type of PV chemistry as it relates to toxicity are covered in subsections a, b, and c in section 1.2.2; on crystalline silicon, cadmium telluride, and CIS/CIGS respectively. The rest of this section applies equally to both silicon and thin film panels.

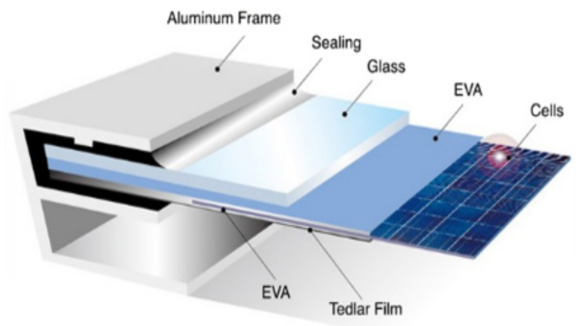


Figure 2: Components of crystalline silicon panels. The vast majority of silicon panels consist of a glass sheet on the topside with an aluminum frame providing structural support. Image Source: www.riteksolar.com.tw

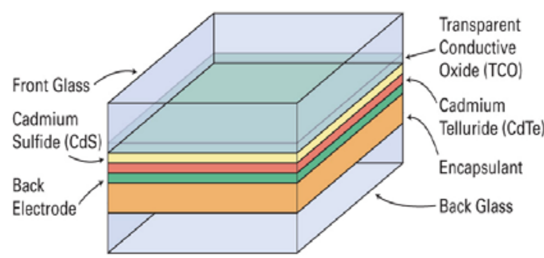


Figure 3: Layers of a common frameless thin-film panel (CdTe). Many thin film panels are frameless, including the most common thin-film panels, First Solar's CdTe. Frameless panels have protective glass on both the front and back of the panel. Layer thicknesses not to scale. Image Source: www.homepower.com

To provide decades of corrosion-free operation, PV cells in PV panels are encapsulated from air and moisture between two layers of plastic. The encapsulation layers are protected on the top with a layer of tempered glass and on the backside with a polymer sheet. Frameless modules include a protective layer of glass on the rear of the panel, which may also be tempered. The plastic ethylene-vinyl acetate (EVA) commonly provides the cell encapsulation. For decades, this same material has been used between layers of tempered glass to give car windshields and hurricane windows their great strength. In the same way that a car windshield cracks but stays intact, the EVA layers in PV panels keep broken panels intact (see Figure 4). Thus, a damaged module does not generally create small pieces of debris; instead, it largely remains together as one piece.

Figure 4: The mangled PV panels in this picture illustrate the nature of broken solar panels; the glass cracks but the panel is still in one piece. Image Source: http://img.alibaba.com/photo/115259576/broken_solar_panel.jpg

PV panels constructed with the same basic components as modern panels have been installed across the globe for well over thirty years.[3] The long-term durability and performance demonstrated over these decades, as well as the results of accelerated lifetime testing, helped lead to an industry-standard 25-year power production warranty for PV panels. These power warranties warrant a PV panel to produce at least 80% of their original nameplate production after 25 years of use. A recent SolarCity and DNV GL study reported that today's quality PV panels should be expected to reliably and efficiently produce power for thirty-five years.[4]

Local building codes require all structures, including ground mounted solar arrays, to be engineered to withstand anticipated wind speeds, as defined by the local wind speed requirements. Many racking products are available in versions engineered for wind speeds of up to 150 miles per hour, which is significantly higher than the wind speed requirement anywhere in North Carolina. The strength of PV mounting structures were demonstrated during Hurricane Sandy in 2012 and again during Hurricane Matthew in 2016. During Hurricane Sandy, the many large-scale solar facilities in New Jersey and New York at that time suffered only minor damage.[5] In the fall of 2016, the US and Caribbean experienced destructive winds and torrential rains from Hurricane Matthew, yet one leading solar tracker manufacturer reported that their numerous systems in the impacted area received zero damage from wind or flooding.[6]

In the event of a catastrophic event capable of damaging solar equipment, such as a tornado, the system will almost certainly have property insurance that will cover the cost to cleanup and repair the project. It is in the best interest of the system owner to protect their investment against such risks. It is also in their interest to get the project repaired and producing full power as soon as possible. Therefore, the investment in adequate insurance is a wise business practice for the system owner. For the same reasons, adequate insurance coverage is also generally a requirement of the bank or firm providing financing for the project.

1.2.2 Photovoltaic (PV) Technologies

a. **Crystalline Silicon**

This subsection explores the toxicity of silicon-based PV panels and concludes that they do not pose a material risk of toxicity to public health and safety. Modern crystalline silicon PV panels, which account for over 90% of solar PV panels installed today, are, more or less, a commodity product. The overwhelming majority of panels installed in North Carolina are crystalline silicon panels that are informally classified as Tier I panels. Tier I panels are from well-respected manufacturers that have a good chance of being able to honor warranty claims. Tier I panels are understood to be of high quality, with predictable performance, durability, and content. Well over 80% (by weight) of the content of a PV panel is the tempered glass front and the aluminum frame, both of which are common building materials. Most of the remaining portion are common plastics, including polyethylene terephthalate in the backsheet, EVA encapsulation of the PV cells, polyphenyl ether in the junction box, and polyethylene insulation on the wire leads. The active, working components of the system are the silicon photovoltaic cells, the small electrical leads connecting them together, and to the wires coming out of the back of the panel. The electricity generating and conducting components makeup less than 5% of the weight of most panels. The PV cell itself is nearly 100% silicon, and silicon is the second most common element in the Earth's crust. The silicon for PV cells is obtained by high-temperature processing of quartz sand (SiO_2) that removes its oxygen molecules. The refined silicon is converted to a PV cell by adding extremely small amounts of boron and phosphorus, both of which are common and of very low toxicity.

The other minor components of the PV cell are also generally benign; however, some contain lead, which is a human toxicant that is particularly harmful to young children. The minor components include an extremely thin antireflective coating (silicon nitride or titanium dioxide), a thin layer of aluminum on the rear, and thin strips of silver alloy that are screen-printed on the front and rear of cell.[7] In order for the front and rear electrodes to make effective electrical contact with the proper layer of the PV cell, other materials (called glass frit) are mixed with the silver alloy and then heated to etch the metals into the cell. This glass frit historically contains a small amount of lead (Pb) in the form of lead oxide. The 60 or 72 PV cells in a PV panel are connected by soldering thin solder-covered copper tabs from the back of one cell to the front of the next cell. Traditionally a tin-based solder containing some lead (Pb) is used, but some manufacturers have switched to lead-free solder. The glass frit and/or the solder may contain trace amounts of other metals, potentially including some with human toxicity such as cadmium. However, testing to simulate the potential for leaching from broken panels, which is discussed in more detail below, did not find a potential toxicity threat from these trace elements. Therefore, the tiny amount of lead in the grass frit and the solder is the only part of silicon PV panels with a potential to create a negative health impact. However, as described below, the very limited amount of lead involved and its strong physical and chemical attachment to other components of the PV panel means that even in worst-case scenarios the health hazard it poses is insignificant.

As with many electronic industries, the solder in silicon PV panels has historically been a lead-based solder, often 36% lead, due to the superior properties of such solder. However, recent advances in lead-free solders have spurred a trend among PV panel manufacturers to reduce or remove the lead in their panels. According to the 2015 Solar Scorecard from the Silicon Valley Toxics Coalition, a group that tracks environmental responsibility of photovoltaic panel manufacturers, fourteen companies (increased from twelve companies in 2014) manufacture PV panels certified to meet the European Restriction of

Hazardous Substances (RoHS) standard. This means that the amount of cadmium and lead in the panels they manufacture fall below the RoHS thresholds, which are set by the European Union and serve as the world's de facto standard for hazardous substances in manufactured goods.[8] The Restriction of Hazardous Substances (RoHS) standard requires that the maximum concentration found in any homogenous material in a produce is less than 0.01% cadmium and less than 0.10% lead, therefore, any solder can be no more than 0.10% lead.[9]

While some manufacturers are producing PV panels that meet the RoHS standard, there is no requirement that they do so because the RoHS Directive explicitly states that the directive does not apply to photovoltaic panels.[10] The justification for this is provided in item 17 of the current RoHS Directive: "The development of renewable forms of energy is one of the Union's key objectives, and the contribution made by renewable energy sources to environmental and climate objectives is crucial. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources (4) recalls that there should be coherence between those objectives and other Union environmental legislation. Consequently, this Directive should not prevent the development of renewable energy technologies that have no negative impact on health and the environment and that are sustainable and economically viable."

The use of lead is common in our modern economy. However, only about 0.5% of the annual lead consumption in the U.S. is for electronic solder for all uses; PV solder makes up only a tiny portion of this 0.5%. Close to 90% of lead consumption in the US is in batteries, which do not encapsulate the pounds of lead contained in each typical automotive battery. This puts the lead in batteries at great risk of leaching into the environment. Estimates for the lead in a single PV panel with lead-based solder range from 1.6 to 24 grams of lead, with 13g (less than half of an ounce) per panel seen most often in the literature.[11] At 13 g/panel[12], each panel contains one-half of the lead in a typical 12-gauge shotgun shell. This amount equates to roughly 1/750th of the lead in a single car battery. In a panel, it is all durably encapsulated from air or water for the full life of the panel.[14]

As indicated by their 20 to 30-year power warranty, PV modules are designed for a long service life, generally over 25 years. For a panel to comply with its 25-year power warranty, its internal components, including lead, must be sealed from any moisture. Otherwise, they would corrode and the panel's output would fall below power warranty levels. Thus, the lead in operating PV modules is not at risk of release to the environment during their service lifetime. In extreme experiments, researchers have shown that lead can leach from crushed or pulverized panels.[15, 16] However, more real-world tests designed to represent typical trash compaction that are used to classify waste as hazardous or non-hazardous show no danger from leaching.[17, 18] For more information about PV panel end-of-life, see the Panel Disposal section.

As illustrated throughout this section, silicon-based PV panels do not pose a material threat to public health and safety. The only aspect of the panels with potential toxicity concerns is the very small amount of lead in some panels. However, any lead in a panel is well sealed from environmental exposure for the operating lifetime of the solar panel and thus not at risk of release into the environment.

b. Cadmium Telluride (CdTe) PV Panels

This subsection examines the components of a cadmium telluride (CdTe) PV panel. Research demonstrates that they pose negligible toxicity risk to public health and safety while significantly reducing the public's exposure to cadmium by reducing coal emissions. As of mid-2016, a few hundred MWs of cadmium telluride (CdTe) panels, all manufactured by the U.S. company First Solar, have been installed in North Carolina.

Questions about the potential health and environmental impacts from the use of this PV technology are related to the concern that these panels contain cadmium, a toxic heavy metal. However, scientific studies have shown that cadmium telluride differs from cadmium due to its high chemical and thermal stability.[19] Research has shown that the tiny amount of cadmium in these panels does not pose a health or safety risk.[20] Further, there are very compelling reasons to welcome its adoption due to reductions in unhealthy pollution associated with burning coal. Every GWh of electricity generated by burning coal produces about 4 grams of cadmium air emissions.[21] Even though North Carolina produces a significant fraction of our electricity from coal, electricity from solar offsets much more natural gas than coal due to natural gas plants being able to adjust their rate of production more easily and quickly. If solar electricity offsets 90% natural gas and 10% coal, each 5-megawatt (5 MW_{AC}, which is generally 7 MW_{DC}) CdTe solar facility in North Carolina keeps about 157 grams, or about a third of a pound, of cadmium *out of* our environment.[22, 23]

Cadmium is toxic, but all the approximately 7 grams of cadmium in one CdTe panel is in the form of a chemical compound cadmium telluride,[24] which has 1/100th the toxicity of free cadmium.[25] Cadmium telluride is a very stable compound that is non-volatile and non-soluble in water. Even in the case of a fire, research shows that less than 0.1% of the cadmium is released when a CdTe panel is exposed to fire. The fire melts the glass and encapsulates over 99.9% of the cadmium in the molten glass.[27]

It is important to understand the source of the cadmium used to manufacture CdTe PV panels. The cadmium is a byproduct of zinc and lead refining. The element is collected from emissions and waste streams during the production of these metals and combined with tellurium to create the CdTe used in PV panels. If the cadmium were not collected for use in the PV panels or other products, it would otherwise either be stockpiled for future use, cemented and buried, or disposed of.[28] Nearly all the cadmium in old or broken panels can be recycled which can eventually serve as the primary source of cadmium for new PV panels.[29]

Similar to silicon-based PV panels, CdTe panels are constructed of a tempered glass front, one instead of two clear plastic encapsulation layers, and a rear heat strengthened glass backing (together >98% by weight). The final product is built to withstand exposure to the elements without significant damage for over 25 years. While not representative of damage that may occur in the field or even at a landfill, laboratory evidence has illustrated that when panels are ground into a fine powder, very acidic water is able to leach portions of the cadmium and tellurium,[30] similar to the process used to recycle CdTe panels. Like many silicon-based panels, CdTe panels are reported (as far back ask 1998[31]) to pass the EPA's Toxic Characteristic Leaching Procedure (TCLP) test, which tests the potential for crushed panels in a landfill to leach hazardous substances into groundwater.[32] Passing this test means that they are classified as non-hazardous waste and can be deposited in landfills.[33, 34] For more information about PV panel end-of-life, see the Panel Disposal section.

There is also concern of environmental impact resulting from potential catastrophic events involving CdTe PV panels. An analysis of worst-case scenarios for environmental impact from CdTe PV panels, including earthquakes, fires, and floods, was conducted by the University of Tokyo in 2013. After reviewing the extensive international body of research on CdTe PV technology, their report concluded, "Even in the worst-case scenarios, it is unlikely that the Cd concentrations in air and sea water will exceed the environmental regulation values."[35] In a worst-case scenario of damaged panels abandoned on the ground, insignificant amounts of cadmium will leach from the panels. This is because this scenario is much less conducive (larger module pieces, less acidity) to leaching than the conditions of the EPA's TCLP test used to simulate landfill conditions, which CdTe panels pass.[36]

First Solar, a U.S. company, and the only significant supplier of CdTe panels, has a robust panel take-back and recycling program that has been operating commercially since 2005.[37] The company states that it is "committed to providing a commercially attractive recycling solution for photovoltaic (PV) power plant and module owners to help them meet their module (end of life) EOL obligation simply, cost-effectively and responsibly." First Solar global recycling services to their customers to collect and recycle panels once they reach the end of productive life whether due to age or damage. These recycling service agreements are structured to be financially attractive to both First Solar and the solar panel owner. For First Solar, the contract provides the company with an affordable source of raw materials needed for new panels and presumably a diminished risk of undesired release of Cd. The contract also benefits the solar panel owner by allowing them to avoid tipping fees at a waste disposal site. The legal contract helps provide peace of mind by ensuring compliance by both parties when considering the continuing trend of rising disposal costs and increasing regulatory requirements.

c. **CIS/CIGS and other PV technologies**

Copper indium gallium selenide PV technology, often referred to as CIGS, is the second most common type of thin-film PV panel but a distant second behind CdTe. CIGS cells are composed of a thin layer of copper, indium, gallium, and selenium on a glass or plastic backing. None of these elements are very toxic, although selenium is a regulated metal under the Federal Resource Conservation and Recovery Act (RCRA).[38] The cells often also have an extremely thin layer of cadmium sulfide that contains a tiny amount of cadmium, which is toxic. The promise of high efficiency CIGS panels drove heavy investment in this technology in the past. However, researchers have struggled to transfer high efficiency success in the lab to low-cost full-scale panels in the field.[39] Recently, a CIGS manufacturer based in Japan, Solar Frontier, has achieved some market success with a rigid, glass-faced CIGS module that competes with silicon panels. Solar Frontier produces the majority of CIS panels on the market today.[40] Notably, these panels are RoHS compliant,[41] thus meeting the rigorous toxicity standard adopted by the European Union even thought this directive exempts PV panels. The authors are unaware of any completed or proposed utility-scale system in North Carolina using CIS/CIGS panels.

1.2.3 Panel End-of-Life Management

Concerns about the volume, disposal, toxicity, and recycling of PV panels are addressed in this subsection. To put the volume of PV waste into perspective, consider that by 2050, when PV systems installed in 2020 will reach the end of their lives, it is estimated that the global annual PV panel waste tonnage will be 10% of the 2014 global e-waste tonnage.[42] In the U.S., end-of-life disposal of solar products is governed by the Federal Resource Conservation and Recovery Act (RCRA), as well as state policies in some situations. RCRA separates waste into hazardous (not accepted at ordinary landfill) and solid waste (generally accepted at ordinary landfill) based on a series of rules. According to RCRA, the way to determine if a PV panel is classified as hazardous waste is the Toxic Characteristic Leaching Procedure (TCLP) test. This EPA test is designed to simulate landfill disposal and determine the risk of hazardous substances leaching out of the landfill.[43,44,45] Multiple sources report that most modern PV panels (both crystalline silicon and cadmium telluride) pass the TCLP test.[46,47] Some studies found that some older (1990s) crystalline silicon panels, and perhaps some newer crystalline silicon panels (specifics are not given about vintage of panels tested), do not pass the lead (Pb) leachate limits in the TCLP test.[48,49]

The test begins with the crushing of a panel into centimeter-sized pieces. The pieces are then mixed in an acid bath. After tumbling for eighteen hours, the fluid is tested for forty hazardous substances that all must be below specific threshold levels to pass the test. Research comparing TCLP conditions to conditions of damaged panels in the field found that simulated landfill conditions provide overly conservative estimates of leaching for field-damaged panels.[50] Additionally, research in Japan has found no detectable Cd leaching from cracked CdTe panels when exposed to simulated acid rain.[51]

Although modern panels can generally be landfilled, they can also be recycled. Even though recent waste volume has not been adequate to support significant PV-specific recycling infrastructure, the existing recycling industry in North Carolina reports that it recycles much of the current small volume of broken PV panels. In an informal survey conducted by the NC Clean Energy Technology Center survey in early 2016, seven of the eight large active North Carolina utility-scale solar developers surveyed reported that they send damaged panels back to the manufacturer and/or to a local recycler. Only one developer reported sending damaged panels to the landfill.

The developers reported at that time that they are usually paid a small amount per panel by local recycling firms. In early 2017, a PV developer reported that a local recycler was charging a small fee per panel to recycle damaged PV panels. The local recycling firm known to authors to accept PV panels described their current PV panel recycling practice as of early 2016 as removing the aluminum frame for local recycling and removing the wire leads for local copper recycling. The remainder of the panel is sent to a facility for processing the non-metallic portions of crushed vehicles, referred to as "fluff" in the recycling industry.[52] This processing within existing general recycling plants allows for significant material recovery of major components, including glass which is 80% of the module weight, but at lower yields than PV-specific recycling plants. Notably almost half of the material value in a PV panel is in the few grams of silver contained in almost every PV panel produced today. In the long-term, dedicated PV panel recycling plants can increase treatment capacities and maximize revenues resulting in better output quality and the ability to recover a greater fraction of the useful materials.[53] PV-specific panel recycling technologies have been researched and implemented to some extent for the past decade, and have been shown to be able to recover over 95% of PV material (semiconductor) and over 90% of the glass in a PV panel.[54]

A look at global PV recycling trends hints at the future possibilities of the practice in our country. Europe installed MW-scale volumes of PV years before the U.S. In 2007, a public-private partnership between the European Union and the solar industry set up a voluntary collection and recycling system called PV CYCLE. This arrangement was later made mandatory under the EU's WEEE directive, a program for waste electrical and electronic equipment.[55] Its member companies (PV panel producers) fully finance the association. This makes it possible for end-users to return the member companies' defective panels for recycling at any of the over 300 collection points around Europe without added costs. Additionally, PV CYCLE will pick up batches of 40 or more used panels at no cost to the user. This arrangement has been very successful, collecting and recycling over 13,000 tons by the end of 2015.[56]

In 2012, the WEEE Directive added the end-of-life collection and recycling of PV panels to its scope.[57] This directive is based on the principle of extended-producer-responsibility. It has a global impact because producers that want to sell into the EU market are legally responsible for end-of-life management. Starting in 2018, this directive targets that 85% of PV products "put in the market" in Europe are recovered and 80% is prepared for reuse and recycling.

The success of the PV panel collection and recycling practices in Europe provides promise for the future of recycling in the U.S. In mid-2016, the US Solar Energy Industry Association (SEIA) announced that they are starting a national solar panel recycling program with the guidance and support of many leading PV panel producers.[58] The program will aggregate the services offered by recycling vendors and PV manufacturers, which will make it easier for consumers to select a cost-effective and environmentally responsible end-of-life management solution for their PV products. According to SEIA, they are planning the program in an effort to make the entire industry landfill-free. In addition to the national recycling network program, the program will provide a portal for system owners and consumers with information on how to responsibly recycle their PV systems.

While a cautious approach toward the potential for negative environmental and/or health impacts from retired PV panels is fully warranted, this section has shown that the positive health impacts of reduced emissions from fossil fuel combustion from PV systems more than outweighs any potential risk. Testing shows that silicon and CdTe panels are both safe to dispose of in landfills, and are also safe in worst case conditions of abandonment or damage in a disaster. Additionally, analysis by local engineers has found that the current salvage value of the equipment in a utility scale PV facility generally exceeds general contractor estimates for the cost to remove the entire PV system.[59, 60, 61]

1.2.4 Non-Panel System Components (racking, wiring, inverter, transformer)

While previous toxicity subsections discussed PV panels, this subsection describes the non-panel components of utility-scale PV systems and investigates any potential public health and safety concerns. The most significant non-panel component of a ground-mounted PV system is the mounting structure of the rows of panels, commonly referred to as "racking". The vertical post portion of the racking is galvanized steel and the remaining above-ground racking components are either galvanized steel or aluminum, which are both extremely common and benign building materials. The inverters that make the solar generated electricity ready to send to the grid have weather-proof steel enclosures that protect the working components from the elements. The only fluids that they might contain are associated with their cooling systems, which are not unlike the cooling system in a computer. Many inverters today are RoHS compliant.

The electrical transformers (to boost the inverter output voltage to the voltage of the utility connection point) do contain a liquid cooling oil. However, the fluid used for that function is either a non-toxic mineral oil or a biodegradable non-toxic vegetable oil, such as BIOTEMP from ABB. These vegetable transformer oils have the additional advantage of being much less flammable than traditional mineral oils. Significant health hazards are associated with old transformers containing cooling oil with toxic PCBs. Transfers with PCB-containing oil were common before PCBs were outlawed in the U.S. in 1979. PCBs still exist in older transformers in the field across the country.

Other than a few utility research sites, there are no batteries on- or off-site associated with utility-scale solar energy facilities in North Carolina, avoiding any potential health or safety concerns related to battery technologies. However, as battery technologies continue to improve and prices continue to decline we are likely to start seeing some batteries at solar facilities. Lithium ion batteries currently dominate the world utility-scale battery market, which are not very toxic. No non-panel system components were found to pose any health or environmental dangers.

1.4 Operations and Maintenance – Panel Washing and Vegetation Control

Throughout the eastern U.S., the climate provides frequent and heavy enough rain to keep panels adequately clean. This dependable weather pattern eliminates the need to wash the panels on a regular basis. Some system owners may choose to wash panels as often as once a year to increase production, but most in N.C. do not regularly wash any PV panels. Dirt build up over time may justify panel washing a few times over the panels' lifetime; however, nothing more than soap and water are required for this activity.

The maintenance of ground-mounted PV facilities requires that vegetation be kept low, both for aesthetics and to avoid shading of the PV panels. Several approaches are used to maintain vegetation at NC solar facilities, including planting of limited-height species, mowing, weed-eating, herbicides, and grazing livestock (sheep). The following descriptions of vegetation maintenance practices are based on interviews with several solar developers as well as with three maintenance firms that together are contracted to maintain well over 100 of the solar facilities in N.C. The majority of solar facilities in North Carolina maintain vegetation primarily by mowing. Each row of panels has a single row of supports, allowing sickle mowers to mow under the panels. The sites usually require mowing about once a month during the growing season. Some sites employ sheep to graze the site, which greatly reduces the human effort required to maintain the vegetation and produces high quality lamb meat.[62]

In addition to mowing and weed eating, solar facilities often use some herbicides. Solar facilities generally do not spray herbicides over the entire acreage; rather they apply them only in strategic locations such as at the base of the perimeter fence, around exterior vegetative buffer, on interior dirt roads, and near the panel support posts. Also unlike many row crop operations, solar facilities generally use only general use herbicides, which are available over the counter, as opposed to restricted use herbicides commonly used in commercial agriculture that require a special restricted use license. The herbicides used at solar facilities are primarily 2-4-D and glyphosate (Round-up®), which are two of the most common herbicides used in lawns, parks, and agriculture across the country. One maintenance firm that was interviewed sprays the grass with a class of herbicide known as a growth regulator in order to slow the growth of grass so that mowing is only required twice a year. Growth regulators are commonly used on highway roadsides and golf courses for the same purpose. A commercial pesticide applicator license is required for anyone other than the landowner to apply herbicides, which helps ensure that all applicators are adequately educated about proper herbicide use and application. The license must be renewed annually and requires passing of a certification exam appropriate to the area in which the applicator wishes to work. Based on the limited data available, it appears that solar facilities in N.C. generally use significantly less herbicides per acre than most commercial agriculture or lawn maintenance services.

2. Electromagnetic Fields (EMF)

PV systems do not emit any material during their operation; however, they do generate electromagnetic fields (EMF), sometimes referred to as radiation. EMF produced by electricity is non-ionizing radiation, meaning the radiation has enough energy to move atoms in a molecule around (experienced as heat), but not enough energy to remove electrons from an atom or molecule (ionize) or to damage DNA. As shown below, modern humans are all exposed to EMF throughout our daily lives without negative health impact. Someone outside of the fenced perimeter of a solar facility is not exposed to significant EMF from the solar facility. Therefore, there is no negative health impact from the EMF produced in a solar farm. The following paragraphs provide some additional background and detail to support this conclusion.

Since the 1970s, some have expressed concern over potential health consequences of EMF from electricity, but no studies have ever shown this EMF to cause health problems.[63] These concerns are based on some epidemiological studies that found a slight increase in childhood leukemia associated with average exposure to residential power-frequency magnetic fields above 0.3 to 0.4 µT (microteslas) (equal to 3.0 to 4.0 mG (milligauss)). µT and mG are both units used to measure magnetic field strength. For comparison, the average exposure for people in the U.S. is one mG or 0.1 µT, with about 1% of the population with an average exposure in excess of 0.4 µT (or 4 mG).[64] These epidemiological studies, which found an association but not a causal relationship, led the World Health Organization's International Agency for Research on Cancer (IARC) to classify ELF magnetic fields as "possibly carcinogenic to humans". Coffee also has this classification. This classification means there is limited evidence but not enough evidence to designate as either a "probable carcinogen" or "human carcinogen". Overall, there is very little concern that ELF EMF damages public health. The only concern that does exist is for long-term exposure above 0.4 µT (4 mG) that may have some connection to increased cases of childhood leukemia. In 1997, the National Academies of Science were directed by Congress to examine this concern and concluded:

> "Based on a comprehensive evaluation of published studies relating to the effects of power-frequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard. Specifically, no conclusive and consistent evidence shows that exposures to residential electric and magnetic fields produce cancer, adverse neurobehavioral effects, or reproductive and developmental effects."[65]

There are two aspects to electromagnetic fields, an electric field and a magnetic field. The electric field is generated by voltage and the magnetic field is generated by electric current, i.e., moving electrons. A task group of scientific experts convened by the World Health Organization (WHO) in 2005 concluded that there were no substantive health issues related to *electric* fields (0 to 100,000 Hz) at levels generally encountered by members of the public.[66] The relatively low voltages in a solar facility and the fact that electric fields are easily shielded (i.e., blocked) by common materials, such as plastic, metal, or soil means that there is no concern of negative health impacts from the electric fields generated by a solar facility. Thus, the remainder of this section addresses magnetic fields. Magnetic fields are not shielded by most common materials and thus can easily pass through them. Both types of fields are strongest close to the source of electric generation and weaken quickly with distance from the source.

The direct current (DC) electricity produced by PV panels produce stationary (0 Hz) electric and magnetic fields. Because of minimal concern about potential risks of stationary fields, little scientific research has examined stationary fields' impact on human health.[67] In even the largest PV facilities, the DC voltages and currents are not very high. One can illustrate the weakness of the EMF generated by a PV panel by placing a compass on an operating solar panel and observing that the needle still points north.

While the electricity throughout the majority of a solar site is DC electricity, the inverters convert this DC electricity to alternating current (AC) electricity matching the 60 Hz frequency of the grid. Therefore, the inverters and the wires delivering this power to the grid are producing non-stationary EMF, known as extremely low frequency (ELF) EMF, normally oscillating with a frequency of 60 Hz. This frequency is at the low-energy end of the electromagnetic spectrum. Therefore, it has less energy than other commonly encountered types of non-ionizing radiation like radio waves, infrared radiation, and visible light.

The wide use of electricity results in background levels of ELF EMFs in nearly all locations where people spend time – homes, workplaces, schools, cars, the supermarket, etc. A person's average exposure depends upon the sources they encounter, how close they are to them, and the amount of time they spend there.[68] As stated above, the average exposure to magnetic fields in the U.S. is estimated to be around one mG or 0.1 µT, but can vary considerably depending on a person's exposure to EMF from electrical devices and wiring.[69] At times we are often exposed to much higher ELF magnetic fields, for example when standing three feet from a refrigerator the ELF magnetic field is 6 mG and when standing three feet from a microwave oven the field is about 50 mG.[70] The strength of these fields diminish quickly with distance from the source, but when surrounded by electricity in our homes and other buildings moving away from one source moves you closer to another. However, unless you are inside of the fence at a utility-scale solar facility or electrical substation it is impossible to get very close to the EMF sources. Because of this, EMF levels at the fence of electrical substations containing high voltages and currents are considered "generally negligible".[71, 72]

The strength of ELF-EMF present at the perimeter of a solar facility or near a PV system in a commercial or residential building is significantly lower than the typical American's average EMF exposure.[73, 74] Researchers in Massachusetts measured magnetic fields at PV projects and found the magnetic fields dropped to very low levels of 0.5 mG or less, and in many cases to less than background levels (0.2 mG), at distances of no more than nine feet from the residential inverters and 150 feet from the utility-scale inverters.[75] Even when measured within a few feet of the utility-scale inverter, the ELF magnetic fields were well below the International Commission on Non-Ionizing Radiation Protection's recommended magnetic field level exposure limit for the general public of 2,000 mG.[76] It is typical that utility scale designs locate large inverters central to the PV panels that feed them because this minimizes the length of wire required and shields neighbors from the sound of the inverter's cooling fans. Thus, it is rare for a large PV inverter to be within 150 feet of the project's security fence.

Anyone relying on a medical device such as pacemaker or other implanted device to maintain proper heart rhythm may have concern about the potential for a solar project to interfere with the operation of his or her device. However, there is no reason for concern because the EMF outside of the solar facility's fence is less than 1/1000 of the level at which manufacturers test for ELF EMF interference, which is 1,000 mG.[77] Manufacturers of potentially affected implanted devices often provide advice on electromagnetic interference that includes avoiding letting the implanted device get too close to certain sources of fields such as some household appliances, some walkie-talkies, and similar transmitting devices. Some manufacturers' literature does not mention high-voltage power lines, some say that exposure in public areas should not give interference, and some advise not spending extended periods of time close to power lines.[78]

3. Electric Shock and Arc Flash Hazards

There is a real danger of electric shock to anyone entering any of the electrical cabinets such as combiner boxes, disconnect switches, inverters, or transformers; or otherwise coming in contact with voltages over 50 Volts.[79] Another electrical hazard is an arc flash, which is an explosion of energy that can occur in a short circuit situation. This explosive release of energy causes a flash of heat and a shockwave, both of which can cause serious injury or death. Properly trained and equipped technicians and electricians know how to safely install, test, and repair PV systems, but there is always some risk of injury when hazardous voltages and/or currents are present. Untrained individuals should not attempt to inspect, test, or repair any aspect of a PV system due to the potential for injury or death due to electric shock and arc flash, The National Electric Code (NEC) requires appropriate levels of warning signs on all electrical components based on the level of danger determined by the voltages and current potentials. The national electric code also requires the site to be secured from unauthorized visitors with either a six-foot chain link fence with three strands of barbed wire or an eight-foot fence, both with adequate hazard warning signs.

4. Fire Safety

The possibility of fires resulting from or intensified by PV systems may trigger concern among the general public as well as among firefighters. However, concern over solar fire hazards should be limited because only a small portion of materials in the panels are flammable, and those components cannot self-support a significant fire. Flammable components of PV panels include the thin layers of polymer encapsulates surrounding the PV cells, polymer backsheets (framed panels only), plastic junction boxes on rear of panel, and insulation on wiring. The rest of the panel is composed of non-flammable components, notably including one or two layers of protective glass that make up over three quarters of the panel's weight.

Heat from a small flame is not adequate to ignite a PV panel, but heat from a more intense fire or energy from an electrical fault can ignite a PV panel.[80] One real-world example of this occurred during July 2015 in an arid area of California. Three acres of grass under a thin film PV facility burned without igniting the panels mounted on fixed-tilt racks just above the grass.[81] While it is possible for electrical faults in PV systems on homes or commercial buildings to start a fire, this is extremely rare.[82] Improving understanding of the PV-specific risks, safer system designs, and updated fire-related codes and standards will continue to reduce the risk of fire caused by PV systems.

PV systems on buildings can affect firefighters in two primary ways, 1) impact their methods of fighting the fire, and 2) pose safety hazard to the firefighters. One of the most important techniques that firefighters use to suppress fire is ventilation of a building's roof. This technique allows superheated toxic gases to quickly exit the building. By doing so, the firefighters gain easier and safer access to the building, Ventilation of the roof also makes the challenge of putting out the fire easier. However, the placement of rooftop PV panels may interfere with ventilating the roof by limiting access to desired venting locations.

New solar-specific building code requirements are working to minimize these concerns. Also, the latest National Electric Code has added requirements that make it easier for first responders to safely and effectively turn off a PV system. Concern for firefighting a building with PV can be reduced with proper fire fighter training, system design, and installation. Numerous organizations have studied fire fighter safety related to PV. Many organizations have published valuable guides and training programs. Some notable examples are listed below.

- The International Association of Fire Fighters (IAFF) and International Renewable Energy Council (IREC) partnered to create an online training course that is far beyond the PowerPoint click-and-view model. The self-paced online course, "Solar PV Safety for Fire Fighters," features rich video content and simulated environments so fire fighters can practice the knowledge they've learned. www.iaff.org/pvsafetytraining
- Photovoltaic Systems and the Fire Code: Office of NC Fire Marshal
- Fire Service Training, Underwriter's Laboratory

- Firefighter Safety and Response for Solar Power Systems, National Fire Protection Research Foundation
- Bridging the Gap: Fire Safety & Green Buildings, National Association of State Fire Marshalls
- Guidelines for Fire Safety Elements of Solar Photovoltaic Systems, Orange County Fire Chiefs Association
- Solar Photovoltaic Installation Guidelines, California Department of Forestry & Fire Protection, Office of the State Fire Marshall
- PV Safety & Firefighting, Matthew Paiss, Homepower Magazine
- PV Safety and Code Development: Matthew Paiss, Cooperative Research Network

Summary

The purpose of this paper is to address and alleviate concerns of public health and safety for utility-scale solar PV projects. Concerns of public health and safety were divided and discussed in the four following sections: (1) Toxicity, (2) Electromagnetic Fields, (3) Electric Shock and Arc Flash, and (4) Fire. In each of these sections, the negative health and safety impacts of utility-scale PV development were shown to be negligible, while the public health and safety benefits of installing these facilities are significant and far outweigh any negative impacts.

[1] Wiser, Ryan, Trieu Mai, Dev Millstein, Jordan Macknick, Alberta Carpenter, Stuart Cohen, Wesley Cole, Bethany Frew, and Garvin A. Heath. 2016. On the Path to SunShot: The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States. Golden, CO: National Renewable Energy Laboratory. Accessed March 2017, www.nrel.gov/docs/fy16osti/65628.pdf

[2] IRENA and IEA-PVPS (2016), "End-of-Life Management: Solar Photovoltaic Panels," International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems.

[3] National Renewable Energy Laboratory, *Overview of Field Experience – Degradation Rates & Lifetimes*. September 14, 2015. Solar Power International Conference. Accessed March 2017, www.nrel.gov/docs/fy15osti/65040.pdf

[4] Miesel et al. *SolarCity Photovoltaic Modules with 35 Year Useful Life.* June 2016. Accessed March 2017. http://www.solarcity.com/newsroom/reports/solarcity-photovoltaic-modules-35-year-useful-life

[5] David Unger. *Are Renewables Stormproof? Hurricane Sandy Tests Solar, Wind.* November 2012. Accessed March 2017. http://www.csmonitor.com/Environment/Energy-Voices/2012/1119/Are-renewables-stormproof-Hurricane-Sandy-tests-solar-wind & http://www.csmonitor.com/Environment/Energy-Voices/2012/1119/Are-renewables-stormproof-Hurricane-Sandy-tests-solar-wind

[6] NEXTracker and 365 Pronto, *Tracking Your Solar Investment: Best Practices for Solar Tracker O&M*. Accessed March 2017. www.nextracker.com/content/uploads/2017/03/NEXTracker_OandM-WhitePaper_FINAL_March-2017.pdf

[7] Christiana Honsberg, Stuart Bowden. *Overview of Screen Printed Solar Cells*. Accessed January 2017. www.pveducation.org/pvcdrom/manufacturing/screen-printed

[8] Silicon Valley Toxics Coalition. *2015 Solar Scorecard.* Accessed August 2016. www.solarscorecard.com/2015/2015-SVTC-Solar-Scorecard.pdf

[9] European Commission. *Recast of Reduction of Hazardous Substances (RoHS) Directive*. September 2016. Accessed August 2016. http://ec.europa.eu/environment/waste/rohs_eee/index_en.htm

[10] Official Journal of the European Union, *DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment.* June 2011. Accessed May 2017. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0065&from=en

[11] Giancarlo Giacchetta, Mariella Leporini, Barbara Marchetti. *Evaluation of the Environmental Benefits of New High Value Process for the Management of the End of Life of Thin Film Photovoltaic Modules.* July 2013. Accessed August 2016. www.researchgate.net/publication/257408804_Evaluation_of_the_environmental_benefits_of_new_high_value_process_for_the_management_of_the_end_of_life_of_thin_film_photovoltaic_modules

[12] European Commission. *Study on Photovoltaic Panels Supplementing The Impact Assessment for a Recast of the Weee Directive.* April 2011. Accessed August 2016. http://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PVs%20Bio%20final.pdf

[14] The amount of lead in a typical car battery is 21.4 pounds. Waste 360. Chaz Miller. *Lead Acid Batteries.* March 2006. Accessed August 2016. http://waste360.com/mag/waste_leadacid_batteries_3

[15] Okkenhaug G. *Leaching from CdTe PV module material results from batch, column and availability tests.* Norwegian Geotechnical Institute, NGI report No. 20092155-00-6-R; 2010

[16] International Journal of Advanced Applied Physics Research. Renate Zapf-Gottwick1, et al. *Leaching Hazardous Substances out of Photovoltaic Modules*. January 2015. Accessed January 2016. www.cosmosscholars.com/phms/index.php/ijaapr/article/download/485/298

[17] ibid

[18] Parikhit Sinha, et al. Evaluation of Potential Health and Environmental Impacts from End-Of-Life Disposal of Photovoltaics, Photovoltaics, 2014. Accessed May 2016

[19] Bonnet, D. and P. Meyers. 1998. *Cadmium-telluride—Material for thin film solar cells.* J. Mater. Res., Vol. 13, No. 10, pp. 2740-2753

[20] V. Fthenakis, K. Zweibel. *CdTe PV: Real and Perceived EHS Risks*. National Center ofr Photovoltaics and Solar Program Review Meeting, March 24-26, 2003. www.nrel.gov/docs/fy03osti/33561.pdf. Accessed May 2017

[21] International Energy Agency Photovoltaic Power Systems Programme. *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*. March 2015. Accessed August 2016. http://iea-pvps.org/index.php?id=315

[22] Data not available on fraction of various generation sources offset by solar generation in NC, but this is believed to be a reasonable rough estimate. The SunShot report entitled The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States analysis contributes significant (% not provided) offsetting of coal-fired generation by solar PV energy in the southeast.

[23] 7 MW_{DC} * 1.5 GWh/MW_{DC} * 25 years * 0.93 degradation factor * (0.1 *4.65 grams/GWh + 0.9*0.2 grams/GWh)

[24] Vasilis Fthenakis. *CdTe PV: Facts and Handy Comparisons.* January 2003. Accessed March 2017. https://www.bnl.gov/pv/files/pdf/art_165.pdf

[25] Kaczmar, S., *Evaluating the Read-Across Approach on CdTe Toxicity for CdTe Photovoltaics*, SETAC North America 32nd Annual Meeting, Boston, MA, November 2011. Available at: ftp://ftp.co.imperial.ca.us/icpds/eir/campo-verde-solar/final/evaluating-toxicity.pdf, Accessed May 2017

[27] V. M. Fthenakis et al, *Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires* Renewable Progress in Photovoltaics: Research and Application: Res. Appl. 2005; 13:1–11, Accessed March 2017, www.bnl.gov/pv/files/pdf/abs_179.pdf

[28] Fthenakis *V.M., Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production*, Renewable and Sustainable Energy Reviews, 8, 303-334, 2004. www.clca.columbia.edu/papers/Life_Cycle_Impact_Analysis_Cadmium_CdTe_Photovoltaic_production.pdf, Accessed May 2017

[29] International Renewable Energy Agency. Stephanie Weckend, Andreas Wade, Garvin Heath. *End of Life Management: Solar Photovoltaic Panels*. June 2016. Accessed November 2016.

[30] International Journal of Advanced Applied Physics Research. Renate Zapf-Gottwick1, et al. *Leaching Hazardous Substances out of Photovoltaic Modules*. January 2015. Accessed January 2016. www.cosmosscholars.com/phms/index.php/ijaapr/article/download/485/298

[31] Cunningham D., Discussion about TCLP protocols, Photovoltaics and the Environment Workshop, July 23-24, 1998, Brookhaven National Laboratory, BNL-52557

[32] Parikhit Sinha, et al. Evaluation of Potential Health and Environmental Impacts from End-Of-Life Disposal of Photovoltaics, Photovoltaics, 2014. Accessed May 2016

[33] Practical Handbook of Photovoltaics: Fundamentals and Applications. T. Markvart and L. Castaner. *Chapter VII-2: Overview of Potential Hazards*. December 2003. Accessed August 2016. https://www.bnl.gov/pv/files/pdf/art_170.pdf

[34] Norwegian Geotechnical Institute. *Environmental Risks Regarding the Use and End-of-Life Disposal of CdTe PV Modules*. April 2010. Accessed August 2016. https://www.dtsc.ca.gov/LawsRegsPolicies/upload/Norwegian-Geotechnical-Institute-Study.pdf

[35] First Solar. Dr. Yasunari Matsuno. December 2013. August 2016. *Environmental Risk Assessment of CdTe PV Systems to be considered under Catastrophic Events in Japan*. http://www.firstsolar.com/-/media/Documents/Sustainability/Peer-Reviews/Japan_Peer-Review_Matsuno_CdTe-PV-Tsunami.ashx

[36] First Solar. Parikhit Sinha, Andreas Wade. *Assessment of Leaching Tests for Evaluating Potential Environmental Impacts of PV Module Field Breakage*. 2015 IEEE

[37] See p. 22 of First Solar, Sustainability Report. Available at: www.firstsolar.com/-/media/First-Solar/Sustainability-Documents/03801_FirstSolar_SustainabilityReport_08MAR16_Web.ashx, Accessed May 2017

[38] 40 CFR §261.24. *Toxicity Characteristic*. May 2017. Accessed May 2017. https://www.ecfr.gov/cgi-bin/text-idx?node=se40.26.261_124&rgn=div8

[39] Office of Energy Efficiency & Renewable Energy. *Copper Indium Gallium Diselenide.* Accessed March 2017. https://www.energy.gov/eere/sunshot/copper-indium-gallium-diselenide

[40] Mathias Maehlum. *Best Thin Film Solar Panels – Amorphous, Cadmium Telluride or CIGS?* April 2015. Accessed March 2017. http://energyinformative.org/best-thin-film-solar-panels-amorphous-cadmium-telluride-cigs/

[41] RoHS tested certificate for Solar Frontier PV modules. TUVRheinland, signed 11.11.2013

[42] International Renewable Energy Agency. Stephanie Weckend, Andreas Wade, Garvin Heath. *End of Life Management: Solar Photovoltaic Panels*. June 2016. Accessed November 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

[43] 40 C.F.R. §261.10. *Identifying the Characteristics of Hazardous Waste and for Listing Hazardous Waste*. November 2016. Accessed November 2016 http://www.ecfr.gov/cgi-bin/text-idx?SID=ce0006d66da40146b490084ca2816143&mc=true&node=pt40.26.261&rgn=div5#sp40.28.261.b

[44] 40 C.F.R. §261.24 *Toxicity Characteristic*. November 2016. Accessed November 2016. http://www.ecfr.gov/cgi-bin/text-idx?SID=ce0006d66da40146b490084ca2816143&mc=true&node=pt40.26.261&rgn=div5#se40.28.261_124

[45] International Renewable Energy Agency. Stephanie Weckend, Andreas Wade, Garvin Heath. *End of Life Management: Solar Photovoltaic Panels*. June 2016. Accessed November 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

[46] TLCP test results from third-party laboratories for REC, Jinko, and Canadian Solar silicon-based panels. Provided by PV panel manufacturers directly or indirectly to authors

[47] Sinovoltaics, *Introduction to Solar Panel Recycling*, March 2014. Accessed October 2016. http://sinovoltaics.com/solar-basics/introduction-to-solar-panel-recycling/

[48] Brookhaven National Laboratory. Vasilis Fthenakis, *Regulations on Photovoltaic Module Disposal and Recycling.* January 29, 2001.

[49] Parikhit Sinha, et al. Evaluation of Potential Health and Environmental Impacts from End-Of-Life Disposal of Photovoltaics, Photovoltaics, 2014.

[50] First Solar. Parikhit Sinha, Andreas Wade. *Assessment of Leaching Tests for Evaluating Potential Environmental Impacts of PV Module Field Breakage.* October 2015. Accessed August 2016. http://www.firstsolar.com/-/media/Documents/Sustainability/PVSC42-Manuscript-20150912--Assessment-of-Leaching-Tests-for-Evaluating-Potential-Environmental-Impa.ashx

[51] First Solar. Dr. Yasunari Matsuno. December 2013. *Environmental Risk Assessment of CdTe PV Systems to be considered under Catastrophic Events in Japan*. http://www.firstsolar.com/-/media/Documents/Sustainability/Peer-Reviews/Japan_Peer-Review_Matsuno_CdTe-PV-Tsunami.ashx

[52] Phone interview, February 3, 2016, TT&E Iron & Metal, Garner, NC www.ncscrapmetal.com/

[53] Wen-His Huang, et al. *Strategy and Technology To Recycle Water-silicon Solar Modules*. Solar Energy, Volume 144, March 2017, Pages 22-31

[54] International Renewable Energy Agency. Stephanie Weckend, Andreas Wade, Garvin Heath. *End of Life Management: Solar Photovoltaic Panels*. June 2016. Accessed November 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

[55] Official Journal of the European Union. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment*. July 2012. Accessed November 2016. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32012L0019

[56] PV CYCLE. *Annual Report 2015*. Accessed November 2016. https://pvcyclepublications.cld.bz/Annual-Report-PV-CYCLE-2015/6-7

[57] Official Journal of the European Union. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment*. July 2012. Accessed November 2016. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32012L0019

[58] SEIA National PV Recycling Program: www.seia.org/seia-national-pv-recycling-program

[59] RBI Solar, Decommissioning Plan submitted to Catawba County associated with permitting of a 5MW solar project in June 2016. Accessed April 2017. www.catawbacountync.gov/Planning/Projects/Rezonings/RZ2015-05_DecommissioningPlan.pdf

[60] Birdseye Renewables, Decommissioning Plan submitted to Catawba County associated with permitting of a 5MW solar project in May 2015. Accessed April 2017. www.catawbacountync.gov/Planning/Projects/Rezonings/RZ2015-04_DecommissioningPlan.pdf

[61] Cypress Creek Renewables, Decommissioning Plan submitted to Catawba County associated with permitting of a 5MW solar project in September 2016. Accessed April 2017. www.catawbacountync.gov/Planning/Projects/Rezonings/RZ2016-06decommission.pdf

[62] Sun Raised Farms: http://sunraisedfarms.com/index.html

[63] National Institute of Environmental Health Sciences and National Institutes of Health, EMF: Electric and Magnetic Fields Associated with Electric Power: Questions and Answers, June 2002

[64] World Health Organization. *Electromagnetic Fields and Public Health: Exposure to Extremely Low Frequency Fields*. June 2007. Accessed August 2016. http://www.who.int/peh-emf/publications/facts/fs322/en/
[65] Committee on the Possible Effects of Electromagnetic Fields on Biologic Systems, National Research Council, Possible Health Effects of Exposure to Residential Electric and Magnetic Fields, ISBN: 0-309-55671-6, 384 pages, 6 x 9, (1997) This PDF is available from the National Academies Press at: http://www.nap.edu/catalog/5155.html
[66] World Health Organization. *Electromagnetic Fields and Public Health: Exposure to Extremely Low Frequency Fields*. June 2007. Accessed August 2016. http://www.who.int/peh-emf/publications/facts/fs322/en/
[67] World Health Organization. *Electromagnetic Fields and Public Health: Static Electric and Magnetic Fields*. March 2006. Accessed August 2016. http://www.who.int/peh-emf/publications/facts/fs299/en/
[68] Asher Sheppard, Health Issues Related to the Static and Power-Frequency Electric and Magnetic Fields (EMFs) of the Soitec Solar Energy Farms, April 30, 2014. Accessed March 2017: www.sandiegocounty.gov/content/dam/sdc/pds/ceqa/Soitec-Documents/Final-EIR-Files/Appendix_9.0-1_EMF.pdf
[69] Massachusetts Clean Energy Center. *Study of Acoustic and EMF Levels from Solar Photovoltaic Projects*. December 2012. Accessed August 2016.
[70] Duke Energy Corporation. *Frequently Asked Questions: Electric and Magnetic Fields*. Accessed August 2016. https://www.duke-energy.com/about-energy/frequently_asked_questions.asp
[71] National Institute of Environmental Health Sciences, *Electric and Magnetic Fields Associate with the use of Electric Power: Questions and Answers*, 2002. Accessed November 2016 www.niehs.nih.gov/health/materials/electric_and_magnetic_fields
[72] Duke Energy Corporation. *Frequently Asked Questions: Electric and Magnetic Fields*. Accessed August 2016. https://www.duke-energy.com/about-energy/frequently_asked_questions.asp
[73] R.A. Tell et al, *Electromagnetic Fields Associated with Commercial Solar Photovoltaic Electric Power Generating Facilities*, Journal of Occupational and Environmental Hygiene, Volume 12, 2015,- Issue 11. Abstract Accessed March 2016: http://www.tandfonline.com/doi/full/10.1080/15459624.2015.1047021
[74] Massachusetts Department of Energy Resources, Massachusetts Department of Environmental Protection, and Massachusetts Clean Energy Center. *Questions & Answers: Ground-Mounted Solar Photovoltaic Systems*. June 2015. Accessed August 2016. http://www.mass.gov/eea/docs/doer/renewables/solar/solar-pv-guide.pdf
[75] Ibid.
[76] Ibid.
[77] *EMFs and medical devices*, Accessed March 2017. www.emfs.info/effects/medical-devices/
[78] ibid.
[79] Damon McCluer. *Electrical Construction & Maintenance: NFPA 70E's Approach to Considering DC Hazards*. September 2013. Accessed October 2016. http://ecmweb.com/safety/nfpa-70e-s-approach-considering-dc-hazards,
[80] Hong-Yun Yang, et. al. *Experimental Studies on the Flammability and Fire Hazards of Photovoltaic Modules, Materials.* July 2015. Accessed August 2016. http://www.mdpi.com/1996-1944/8/7/4210/pdf
[81] Matt Fountain. The Tribune. *Fire breaks out at Topaz Solar Farm*. July 2015. Accessed August 2016. www.sanluisobispo.com/news/local/article39055539.html
[82] Cooperative Research Network. Matthew Paiss. *Tech Surveillance: PV Safety & Code Developments*. October 2014. Accessed August 2016. http://www.nreca.coop/wp-content/uploads/2013/06/ts_pv_fire_safety_oct_2014.pdf

Published by the N.C. Clean Energy Technology Center at N.C. State University

NC CLEAN ENERGY
TECHNOLOGY CENTER

May 2003 • NREL/CP-520-33561

Conference Paper

CdTe PV: Real and Perceived EHS Risks

V. Fthenakis
National PV EHS Assistance Program

K. Zweibel
National Renewable Energy Laboratory

*Presented at the National Center for Photovoltaics and Solar Program Review Meeting
Denver, Colorado
March 24-26, 2003*

National Renewable Energy Laboratory

**1617 Cole Boulevard
Golden, Colorado 80401-3393**

**NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel**

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

CdTe PV: Real and Perceived EHS Risks

Vasilis Fthenakis[1] and Ken Zweibel[2]
[1]National PV EHS Assistance Program, Brookhaven National Laboratory, Bldg. 830, Upton, NY 11973
[2]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401

ABSTRACT

As CdTe photovoltaics reached commercialization, questions were raised about potential cadmium emissions from CdTe PV modules. Some have attacked the CdTe PV technology as unavoidably polluting the environment, and made comparisons of hypothetical emissions from PV modules to cadmium emissions from coal-fired power plants. This paper gives an overview of the technical issues pertinent to these questions and further explores the potential of environmental, health, and safety (EHS) risks during production, use, and decommissioning of CdTe PV modules. The following issues are discussed: (a) the physical and toxicological properties of CdTe, (b) comparisons of Cd use in CdTe PV with its use in other technologies and products, and (c) the possibility of CdTe releases from PV modules.

1. Toxicology of CdTe

Elemental cadmium, which forms CdTe when reacted with tellurium (Te), is a lung carcinogen, and long-term exposures can cause detrimental effects on kidney and bone. Very limited data exist on CdTe toxicology, and no comparisons with the element Cd have been made [1]. However, CdTe is a more stable and less soluble compound than Cd and, therefore, is probably less toxic than Cd. However, OSHA groups all Cd compounds together, and as a general guidance, all facilities working with any such compounds should control the indoor concentrations of CdTe dust or fumes to below the Permissible Exposure Level-Time Weighted Average (PEL-TWA) Cd concentration of 0.005 mg/m^3.

The U.S. CdTe PV industry is vigilant in preventing health risks and has established proactive programs in industrial hygiene and environmental control. Workers' exposure to cadmium compounds in PV manufacturing facilities is controlled by rigorous industrial hygiene practices and is monitored by frequent medical tests. Results of years of biomonitoring have shown that there are no significant observed increases in levels of worker exposure [2].

2. Amount of Cd Compounds Encapsulated in CdTe Modules and NiCd Batteries

The amount of Cd compounds in PV modules is proportional to the area of the module and the thickness of the CdTe and CdS layers. Most CdTe layers are about 1-3 microns thick, and most CdS layers are about 0.2 microns thick. Therefore, about 3–9 g/m^2 Cd is contained in CdTe, and less than 1 g/m^2 is contained in CdS. A reasonable average amount would be about 7 g/m^2 Cd in CdTe modules. Layer thickness is expected to be reduced as research and development efforts continue, further reducing the amount of Cd compounds in the cells [3].

A CdTe module of 10% sunlight-to-electricity conversion efficiency produces about 100 W of output under standard sunlight conditions. So, there is an average of 7 g/100 W = 70 g per kW of electric power produced. In an average solar location in the United States, such as Kansas, a one-square-meter, 10%-efficient CdTe module containing 7 g of Cd would produce about 5400 kWh over its expected service life of 30 years. That is about 770 kWh per gram of Cd, or 0.001 g/kWh. (Note, this amount is in the module and is not an emission. It can be completely recycled.)

Table 1 shows a comparison of the Cd content in CdTe PV and in NiCd batteries. CdTe modules occupying 1 m^2 contain less Cd than one C–size flashlight battery. A 1-kW system would contain as much Cd as seven C-size batteries. On a per kWh basis, assuming that a NiCd battery can be recharged 700 to 1200 times over its life [4], it would produce an average of 0.046 kWh per g of its weight, which corresponds to 0.306 kWh per g of Cd contained in the battery. This is 2,500 times less than a CdTe PV module. Thus the value of using Cd in PV is much greater than its value elsewhere in the marketplace.

Table 1. Cd Content in CdTe PV and NiCd Batteries

	g/unit	g/kW (ton/GW)	mg/kWh (kg/GWh)
PV CdTe	7 g/m2	70	1.3
NiCd battery -C size	10		3265.

3. EHS Risks during Cadmium Mining

CdTe is manufactured from pure Cd and Te, both of which are by-products of smelting prime metals (e.g., Cu, Zn, Pb, and Au). About 80% of the world's production of cadmium is generated as a by-product of smelting zinc ores. Its major feedstock, sphalerite (ZnS), contains about 0.25% Cd. Secondary cadmium is produced from recycling spent NiCd batteries and other scrap. The demand of zinc has been steadily increasing for decades as driven by economic growth. Therefore, cadmium (in impure form) is produced regardless of its use. Cadmium is used primarily (~65%) in nickel-cadmium rechargeable batteries, paint pigments (~17%), plastic stabilizers (~10%), metal plating (~5%), and metal solders (~2%). When there is no cost-effective market for the metal, raw Cd is disposed of [5].

The total Cd use in the United States was 2,600 tons in 1997; globally, the total use is 19,000 to 20,000 tons. Using only 3% of the U.S. consumption of cadmium (i.e., 78 tons) in the manufacture of CdTe solar cells would generate over 1 GW of new PV per year. Note that the total current PV capacity in the United States is only 0.3 GW and is projected to grow (under optimistic assumptions) to about 3.2 GW/yr by 2020. Even if we envision PV production that is an order of magnitude higher, it would require only about a third of the current U.S. Cd consumption. Yet to change the world's energy infrastructure with CdTe PV, much less Cd would be needed, and it would not impact the overall smelting of Cd at all. In fact, it would provide a beneficial use of Cd that could otherwise be cemented or end up in a waste dump.

4. EHS Risks in CdTe PV Manufacture

In production facilities, workers may be exposed to Cd compounds through the air if contaminated, and by ingestion from hand-to-mouth contact. Inhalation is probably the most important pathway, because of the larger potential for exposure and higher absorption efficiency of Cd compounds through the lung than through the gastrointestinal tract. Processes in which Cd compounds are used or produced in the form of fine particulates or vapor present larger hazards to health. Hazards to workers may arise from feedstock preparation, fume/vapor leaks, etching of excess materials from panels, maintenance operations (e.g., scraping and cleaning), and during waste handling. Caution must be exercised when working with this material, and several layers of control must be implemented to prevent exposure of the employees. In general, the hierarchy of controls includes engineering controls, personal protective equipment, and work practices. The U.S. industry is vigilant in preventing health risks, and has established proactive programs in industrial hygiene and environmental control. Workers' exposure to cadmium in PV manufacturing facilities is controlled by rigorous industrial hygiene practices and is continuously monitored by medical tests, thus preventing health risks [2].

5. Can CdTe from PV Modules Harm Our Health or the Environment?

Toxic compounds cannot cause any adverse health effects unless they enter the human body in harmful doses. The only pathways by which people might be exposed to PV compounds from a finished module are by accidentally ingesting flakes or dust particles, or inhaling dust and fumes. The thin CdTe/CdS layers are stable and solid and are encapsulated between thick layers of glass. Unless the module is purposely ground to a fine dust, dust particles cannot be generated. The vapor pressure of CdTe at ambient conditions is zero. Therefore, it is impossible for any vapors or dust to be generated when using PV modules.

The only issue of some concern is the disposal of the well-encapsulated, relatively immobile CdTe at the end of the modules' useful life. Thin CdTe PV end-of-life or broken modules pass Federal (TCLP-RCRA) leaching criteria for non-hazardous waste [6]. Therefore, according to current laws, such modules could be disposed of in landfills. However, recycling PV modules offers an important marketing advantage, and the industry is considering it as they move toward large and cost-effective production [7,8]. This issue of recycling is not unique to CdTe. The disposal of current x-Si modules, most of which incorporate Pb-based solder, presents similar concerns. Recycling the modules at the end of their useful life completely resolves any environmental concerns.

6. Do CdTe Modules Present Additional Health Risks during a Fire?

The flame temperatures in typical U.S. residential fires are not high enough to vaporize CdTe; flame temperatures in roof fires are in the 800^o–900^oC range, and, in basement rooms, in the 900^o–1000^oC range [9]. The melting point of CdTe is 1041^oC, and evaporation starts at 1050 ^oC. Sublimation occurs at lower temperatures, but the vapor pressure of CdTe at 800 ^oC is only 2.5 torr (0.003 atm). The melting point of CdS is 1750^oC, and its vapor pressure due to sublimation is only 0.1 torr at 800^oC. Preliminary studies at Brookhaven [10] and at the GSF Institute of Chemical Ecology in Germany [11] showed that CdTe releases are unlikely to occur during residential fires or during accidental breakage. The thin layers of CdTe and CdS are sandwiched between glass plates; at typical flame temperatures (800^o–1000°C), these compounds would be encapsulated inside the molten glass so that any Cd vapor emissions would be unlikely. In any case, the fire itself and other sources of emissions within the burning structure are expected to pose an incomparably greater hazard than any potential Cd emissions from PV systems.

7. CdTe PV Can Prevent Cd Emissions from Coal-Burning Power Plants

Coal-burning routinely generates Cd, because Cd is contained in the coal. A typical U.S. coal-power plant will generate waste in the form of fine dust or cake, containing about 140 g of Cd, for every GWh of electricity produced. In addition, a minimum of 2 g of Cd will be emitted from the stack (for plants with perfectly maintained electrostatic precipitators or bag-houses operating at 98.6% efficiency, and median concentration of Cd in U.S. coal of 0.5 ppm) [12]. Power plants with less efficient pollution controls will produce more Cd in gaseous form. Furthermore, a typical U.S. coal-power plant emits about 1000 tons of CO_2, 8 tons of SO_2, 3 tons of NOx, and 0.4 tons of particulates per GWh of electricity produced. All these emissions will be avoided when PV replaces coal-burning for some fraction of electricity generation.

8. Conclusion

The potential EHS risks related to the cadmium content of CdTe PV modules were highlighted for all the different phases of a large-scale implementation of the technology. The basic conclusions are:

<u>Cd Mining:</u> Cadmium is produced primarily as a by-product of zinc production. Because Zn is produced in large quantities, substantial quantities of cadmium is generated as a by-product, no matter how much Cd is used in PV, and can either be put to *beneficial* uses or *discharged* into the environment. When the market does not absorb the Cd generated by metal smelters/refiners, it is cemented and buried, stored for future use, or disposed of to landfills as hazardous waste. Arguably, encapsulating cadmium as CdTe in PV modules presents a safer use than its current uses and is much preferred to disposing it off.

<u>CdTe PV Manufacture</u>: In CdTe PV production facilities, workers may be exposed to Cd compounds through the air they breathe and by ingestion from hand-to-mouth contact. These are real risks and continuing vigilance is required. However, current industrial practice suggests that these risks can be managed and controlled successfully.

<u>CdTe PV Use</u>: No emissions of any kind can be generated when using PV modules under normal conditions. Any comparisons made with cadmium emissions from coal fired power plants are erroneous, because they compare potential accidental emissions from PV systems to routine (unavoidable) emissions from modern coal-fired plants. In reality, PV, when it replaces coal-burning for electricity generation, will prevent Cd emissions in addition to preventing large quantities of CO_2, SO_2, NOx, and particulate emissions.

Related to NiCd batteries, a CdTe PV module uses Cd about 2500 times more efficiently in producing electricity. A 1-kW CdTe PV system contains as little cadmium as seven size-C NiCd batteries. Thus the incremental risk to the house occupants or firefighters from roof fires is negligible. In addition, it is unlikely that CdTe will vaporize during residential fires because the flames are not hot enough. In any case, the fire itself would pose a much greater hazard than any potential Cd emissions from PV systems.

<u>CdTe PV Decommissioning:</u> The only environmental issue is what to do with the modules about 30 years later, if they are no longer useful. Although cadmium telluride is encapsulated between sheets of glass and is unlikely to leach out, the PV industry is considering recycling of these modules at the end of their useful life. Recycling will completely resolve any environmental concerns.

In conclusion, the environmental risks from CdTe PV are minimal. Every energy source or product may present some environmental, health, and safety hazards, and those of CdTe are by no means barriers to scaling-up the technology.

REFERENCES

[1] Fthenakis V., Morris S., Moskowitz P., and Morgan D., "Toxicity of cadmium telluride, copper indium diselenide, and copper gallium diselenide," *Progress in Photovoltaics*, 7, 489-497, 1999.

[2] Bohland J. and Smigielski K., "First Solar's CdTe module manufacturing experience; environmental, health and safety results," *Proceedings of the 28th IEEE Photovoltaic Specialists Conference, Anchorage, AK, September 2000.*

[3] Zweibel K., "Issues in thin film PV manufacturing cost reduction," *Solar Energy Materials and Solar Cells*, 59, 1-18, 1999.

[4] Morrow H., "The Importance of recycling to life cycle analysis of nickel cadmium batteries," *Proceedings of the 8th International Nickel Cadmium Battery Conference, Prague, Czech Republic, September 21-22, 1998.*

[5] Plachy J., *U.S. Geological Survey Minerals Yearbook*, Cadmium-Chapter 17, 2001.

[6] Cunningham D., Discussion about TCLP protocols, *Photovoltaics and the Environment Workshop, July 23-24, 1998,* Brookhaven National Laboratory, BNL-52557.

[7] Bohland J., Dapkus T., Kamm K., and Smigielski K., "Photovoltaics as hazardous materials: the recycling solution," *Proceedings of the 2nd IEEE World Photovoltaic Specialists Conference, pp. 716-719, 1998.*

[8] Fthenakis V., "End-of-life management and recycling of PV modules," *Energy Policy Journal*, 28, 1051-1059, 2000.

[9] Drysdale D., *An Introduction to Fire Dynamics*, pp. 329-330, Wiley, NY, 1985.

[10] Moskowitz P. and Fthenakis V., "Toxic materials released from photovoltaic modules during fires; health risks," *Solar Cells*, 29, 63-71, 1990.

[11] Steinberger H., HSE for CdTe and CIS thin film module operation, IEA expert workshop, *Environmental aspects of PV power systems, May 23, 1997,* Report No. 97072, Niewlaar E. and Alsema E. (ed.), Utrecht University, The Netherlands.

[12] Electric Power Research Institute (EPRI), PISCES data base for US power plants and US coal, copyright EPRI 2002.

3

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE May 2003	3. REPORT TYPE AND DATES COVERED Conference Paper

4. TITLE AND SUBTITLE
CdTe PV: Real and Perceived EHS Risks

5. FUNDING NUMBERS
PVP3.5001

6. AUTHOR(S)
V. Fthenakis* and K. Zweibel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
*National PV EHS Assistance Program; Brookhaven National Laboratory; Bldg. 830; Upton, NY 11973
National Renewable Energy Laboratory; 1617 Cole Blvd.; Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-520-33561

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
As CdTe photovoltaics reached commercialization, questions have been raised about potential cadmium emissions from CdTe PV modules. Some have attacked the CdTe PV technology as unavoidably polluting the environment, and made comparisons of hypothetical emissions from PV modules to cadmium emissions from coal fired power plants. This paper gives an overview of the technical issues pertinent to these questions and further explores the potential of EHS risks during production, use and decommissioning of CdTe PV modules. The following issues are discussed: (a) The physical and toxicological properties of CdTe, (b) comparisons of Cd use in CdTe PV with its use in other technologies and products, and the (c) the possibility of CdTe releases from PV modules.

14. SUBJECT TERMS
cadmium telluride; ES&H; manufacturing; solar cells; thin films

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2005; **13**:713–723
Published online 6 May 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/pip.624

Broader Perspectives

Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires‡

V. M. Fthenakis[1*,†], M. Fuhrmann[1], J. Heiser[1], A. Lanzirotti[2], J. Fitts[1] and W. Wang[1]
[1]*Environmental Sciences Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[2]*Consortium for Advanced Radiation Resources, Univ. of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA*

Fires in residential and commercial properties are not uncommon. If such fires involve the roof, photovoltaic arrays mounted on the roof will be exposed to the flames. The amount of cadmium that can be released in fires involving CdTe PV and the magnitude of associated health risks has been debated. The current study aims in delineating this issue. Previous thermogravimetric studies of CdTe, involved pure CdTe and single-glass PV modules. The current study is based on glass–glass CdTe PV modules which are the only ones in the market. Pieces of commercial CdTe photovoltaic (PV) modules, sizes 25 × 3 cm, were heated to temperatures up to 1100°C to simulate exposure to residential and commercial building fires. The temperature rate and duration in these experiments were defined according to standard protocols. Four different types of analysis were performed to investigate emissions and redistribution of elements in the matrix of heated CdTe PV modules: (1) measurements of sample weight loss as a function of temperature; (2) analyses of Cd and Te in the gaseous emissions; (3) Cd distribution in the heated glass using synchrotron X-ray fluorescence microprobe analysis; and (4) chemical analysis for Cd and Te in the acid-digested glass. These experiments showed that almost all (i.e., 99·5%) of the cadmium content of CdTe PV modules was encapsulated in the molten glass matrix; a small amount of Cd escaped from the perimeter of the samples before the two sheets of glass melted together. Adjusting for this loss in full-size modules, results in 99·96% retention of Cd. Multiplying this with the probability of occurrence for residential fires in wood-frame houses in the US (e.g., 10^{-4}), results in emissions of 0·06 mg/GWh; the probability of sustained fires and subsequent emissions in adequately designed and maintained utility systems appears to be zero. Published in 2005 by John Wiley & Sons, Ltd.

KEY WORDS: CdTe; photovoltaics; LCA; life-cycle assessment; fire emissions; cadmium; leaching; ion-exchange

* Correspondence to: Vasilis Fthenakis, Brookhaven National Laboratory, Building 830, Upton, NY 11973, USA.
† E-mail: vmf@bnl.gov

Contract/grant sponsor: US Department of Energy; contract/grant number: DE-AC02-76CH000016.

Received 4 October 2004
Revised 21 January 2005

1. INTRODUCTION

In the United States, about 1 in 10 000 wood-frame houses may catch fire during the year. If such fires involve the roof, photovoltaic arrays that are mounted there would be exposed to the flames. There are no studies in the literature regarding fire effects on a utility scale PV system, and we are not aware of a reported fire in any utility PV system. Tucson Electric in Arizona, US, has experienced two cases of incorrect wiring that each caused melting of a glass module, and also three cases of small fires in metal DC terminal boxes due to bad connections, but none of these incidents caused a fire to the rest of the field. In addition there were six documented lighting strikes on PV arrays, none of which resulted in a fire. Overall, due to the lack of combustible materials, the risk of a fire that could consume a utility array is extremely small. There is a risk of fire from external fuel sources (e.g., grass/bush fires), but this is controlled through design and operational practices (e.g., metal enclosures of potential ignition sources, firebreaks, controlling vegetation, limited access). Therefore, our study was designed to simulate the potential of toxic emissions only from roof-mounted photovoltaic arrays.

Previous thermogravimetric studies of CdTe at the GSF Institute of Chemical Ecology in Munich, Germany, involved pure CdTe and a small number of tests on single glass PV modules.[1,2] The pure CdTe tests showed a small weight increase between 570 and 800°C, possibly due to oxidation. The oxidized product remained stable until about 1050°C, above which the compound began to vaporize.[2] Other experiments at non-oxidizing conditions (Ar atmosphere), showed a high loss of CdTe in the 900–1050°C range. No experiments involving CdTe encapsulated between two sheets of glass are reported.

The current study is based on glass–CdTe–glass PV modules, which are the only ones in the market. (Single-glass panels are not considered by any manufacturer at this time). Pieces of commercial CdTe photovoltaic (PV) modules, approximately 25 $\times$ 3 cm, were heated to temperatures up to about 1100°C to simulate exposure to residential fires. The heating rate and duration in these experiments were defined according to standard Underwriters Laboratories (UL)[3] and American Society for Testing and Materials (ASTM)[4] test protocols. The total mass loss was calculated by weight measurements. The amounts of Cd and Te releases to the atmosphere were calculated by capturing these elements in solutions of nitric acid or hydrochloric acid and hydrogen peroxide. Also, the distribution of Cd in the burnt pieces was measured with synchrotron X-ray microprobe analysis.

2. CdTe PV MODULE THERMAL CHARACTERISTICS

The composition of the tested samples is shown in Table I. These samples were cut from standard commercial modules produced by First Solar Inc. of Toledo, Ohio. The frames, rails and wires were not included in the experiments. The concentration of the metals was determined by grinding a control piece and leaching in acid/oxidizer solution; these were also cross-referenced with mass balance calculations at the manufacturing plant scale. The concentrations of the glass and ethylene vinyl acetate (EVA) are based on weight measurements.

Table I. Composition of samples

Compound	wt (%)
Total glass	96·061
EVA	2·614
Total Cd	0·059*
Total Te	0·063*
Total Cu	0·011*
Other	1·192

*The uncertainty of these measurements is 5% as determined by ICP analysis.

Table II. CdTe vapor pressure coefficients for equation (2)

A	*B*	*T* (K)	Reference
−9500	6·427	731–922	7
−11 493	7·99	1085–1324	8
−9764	6·572	773–1010	9
−10 000	6·823	1053–1212	10

The EVA is expected to either burn or decompose at approximately 450°C according to experiments involving EVA and back surface sheet on crystalline Si cells.[5]

The module's substrate and front cover are sheets of glass, which has a softening point of 715°C. The following compounds are present or can be formed during the heating (CdTe, CdS, CdO, TeO_2, TeO_4, $CdCl_2$ and $CuCl_2$); other oxides may also be formed. Some of these compounds produce vapors by sublimation at temperatures below their melting points.

The sublimation of pure CdTe is described by the reaction:[6]

$$CdTe(s) = Cd(g) + 0{\cdot}5Te_2(g) \tag{1}$$

The vapor pressure due to sublimation of CdTe is estimated by the Antoine equation:

$$\log P(\text{atm}) = AT^{-1} + B \tag{2}$$

Values for the coefficients *A* and *B* are shown in Table II.

As shown by the CdTe curves in Figure 1, these four sets of coefficients give approximately the same vapor pressure estimates.

The vapor pressure of pure CdS and TeO_2 can be estimated by the following equation[11,12]

$$\log P(\text{mm Hg}) = A + BT^{-1} + C\log T + DT + ET^2 \tag{3}$$

where the constants *A*, *B*, *C*, *D* and *E* are listed in Table III.

As shown in Figure 1, CdS has the lowest vapor pressure of the considered pure cadmium compounds. The vapor pressure of CdTe is two orders of magnitude lower than that of $CdCl_2$ in the temperature range of our experiments. The CdTe pressure due to sublimation at 800°C is about 2·4 torr.

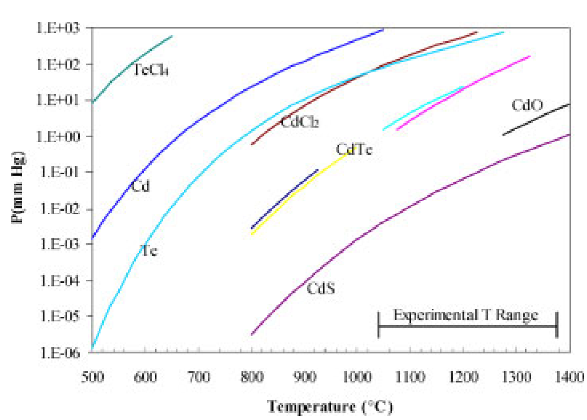


Figure 1. Vapor pressure of cadmium compounds

Table III. Vapor pressure coefficients for equation (3)

Component	*A*	*B*	*C*	*D*	*E*	*T*(K)
CdS(s)	16·06	−11 460	−2·5	—	—	298–1203
$CdCl_2$(s)	17·46	−9270	−2·11	—	—	298–840
$CdCl_2$(l)	25·907	−9183	−5·04	—	—	840–1233
CdO(s)	42·8498	−1 5 443	−10·651	$2{\cdot}0645 \times 10^{-3}$	$-1{\cdot}704 \times 10^{-7}$	1273–1832
TeO_2(s)	23·51	−13 940	−3·52	—	—	298–10 006
$TeCl_4$	225·5681	−13 194	−80·8999	$4{\cdot}5316 \times 10^{-2}$	$-1{\cdot}044 \times 10^{-5}$	506–665

3. THERMOGRAVIMETRIC TESTS

Typical flame temperatures in residential fires are in the 800–900°C range for roof fires and 900–1000°C in fires involving the whole house as measured in basement rooms.[13] In this study we extended this range to the limit of our heating apparatus, which was 1100°C.

3.1. Protocol

There are several validated fire test methods used by the industry and the government in evaluating flammability and fire resistance of materials. Two test methods which are applicable to our task are the Underwriters Laboratories Inc., UL Standard 1256 for Fire Test of Roof Deck Constructions,[3] and the American Society for Testing and Materials (ASTM) Standard E119-98 for Fire Tests of Building Construction and Materials.[4] The later is also adopted by the Uniform Building Code as UBC Standard 7-1. The UL 1256 Standard involves direct fire heating at 760°C, for 30 min. The ASTM Standard involves gradual heating controlled to conform to the standard time–temperature curve shown in Figure 2. Our tests were done in a tube furnace where we adjusted the heating rate to exactly follow this standard temperature rate curve. Pieces of commercial CdTe photovoltaic (PV) modules, nominally 25 × 3 cm were used. The furnace was heated by electrical resistance and contained three zones, so uniformity of the central heated zone was accomplished. The pieces of PV module were placed on alumina plates and were positioned inside a quartz tube in the central uniform-temperature zone of the oven. The tube was fitted with an inlet and outlet for gas flow and was sealed from the outside atmosphere. Air was introduced into the furnace at a rate of 10 l/min, producing a linear velocity of 0·04 m/s above the sample. The airflow carried any released vapor/aerosols from the PV sample to the outlet. The effluent flow was passed through a glass-wool filter and two bubbler-scrubbers in series containing a 0·01 M nitric acid solution in order to capture the Cd and Te releases from the PV module. The quartz tube and glass-wool were leached for 24 h in nitric acid. Complete removal of the metals from the glass-wool filters was verified by additional leaching using hydrochloric acid and hydrogen peroxide solutions for 48 h in a tumbling machine.

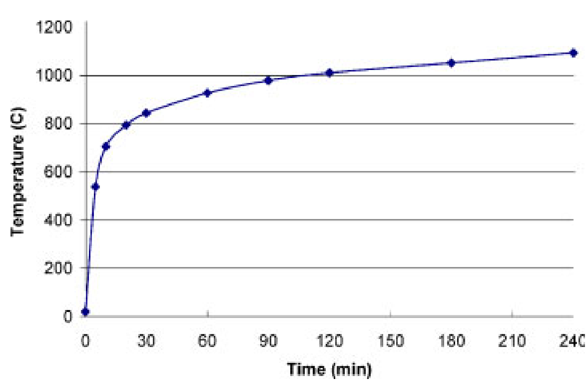


Figure 2. Temperature and heating duration for each experiment (as per ASTM E119-98 Standard)

Table IV. Measured loss of mass

Test	T (°C)	Weight loss (% sample)	Cd emissions (g/m^2)	Cd emissions (% of Cd content)	Te emissions (g/m^2)	Te emissions (% of Te content)
1	760	1·9	0·056	0·6	0·046	0·4
2	900	2·1	0·033	0·4	0·141	1·2
3	1000	1·9	0·048	0·5	1·334	11·6
4	1100	2·2	0·037	0·4	2·680	22·5

3.2. Results

The PV samples were weighed before and after each experiment. Weight loss in the range of 1·9–2·2% of the total weight was recorded (Table IV). Observations of black residues in the reactor walls and filters indicate that most of this weight loss was caused by the decomposition and vaporization of EVA.

The acidic solutions from rinsing of the reactor walls, rinsing of the glass-wool filters in the reactor exhaust, and the scrubber liquids, were analyzed for Cd and Te by inductively coupled plasma (ICP) optical emission spectroscopy (Varian Liberty 100). A small loss of Cd amounting to 0·4–0·6% of the total Cd in the sample was recorded (Table IV). The loss of Te was also very small during heating at 760 and 900°C, but it increased significantly at higher temperatures.

Measurements of the total mass of Cd and Te in the untreated sample were obtained by breaking the sample and leaching the metal content in a tumbling machine with a solution of sulfuric acid and hydrogen peroxide. Complete leaching of the metals was verified by leaching with hydrochloric acid/H_2O_2 solutions. The uncertainty of the ICP analysis was determined with frequent calibration to be $\leq 5\%$.

4. MICROBEAM X-RAY FLUORESENCE ANALYSES

Figure 3 shows an unheated (control) sample and Figure 4 shows the samples heated at 900, 1000 and 1100°C. In these tests it was visually evident that the glass sheets melted together. As will be shown in Figures 6 and 7, such 'soldering' did not occur at the 760°C experiment. Slices 1 mm thick were cut (vertically) from the center and the sides of the samples and were analyzed by microbeam X-ray fluorescence at beamline X26A at the National Synchrotron Light Source (NSLS) of Brookhaven National Laboratory.

4.1. Method

The intensity of the X-ray beam produced at the NSLS is approximately 10 000 times greater than that produced by conventional laboratory X-ray sources. The X-ray beam also has a very small angular divergence due to the small cross-section of the electron source, and therefore, intense X-ray beams of the order of 5–10 μm diameter can be produced using focusing optics. The X26A beamline at the NSLS was used for these experiments. The beam was tuned to 26·8 keV using a Si (111) monochrometer. This energy allowed excitation of Cd but not Te. Data were collected for Cd, Ca, Zr, and Sr Kα fluorescence. The spot size was focused to 30×30 μm using Rh coated Kirckpatrick–Baez mirrors. Energy dispersive SXRF data were collected using a Canberra SL30165

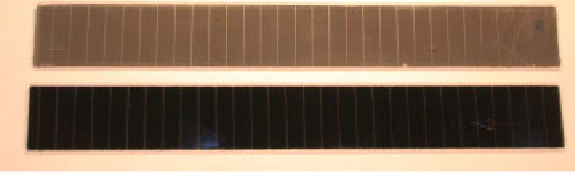


Figure 3. Top and bottom of an unheated sample

Figure 4. (a) Sample after being heated up to 900°C for 1 h; (b) after being heated up to 1000°C for 2 h; (c) after being heated up to 1100°C for 3 h

Si(Li) detector. Incident beam flux was monitored using an ion chamber and changes in fluorescent count rate with time were corrected by normalizing to the ion chamber current values.

Samples were 1-mm-thick slices of the coupons. They were mounted on Kapton tape and placed in a slide holder, with the sample directly exposed to the beam for analysis. Data were collected in two ways. Line scans were collected at step sizes that ranged between 20 and 50 μm, depending on line length. Count times ranged from 5 to 10 s/pixel. Data are shown as normalized Cd counts.

4.2. Results

Figure 5 shows Cd counts along a line scan collected across a slice cut from the control (unheated) sample. The Cd counts in the junction between the two sheets of glass reach a maximum of 50 000 while the Zr counts (indicative of the glass) in the same region are close to zero. Figure 6 shows the Cd line scans collected across the center and edges of a slice cut from the middle of the 760°C PV sample. The Cd count distribution in the center was approximately the same as the distribution in the unheated sample, whereas the distribution near the edges of the PV shows diffusion of Cd in a wider area. Microscopic analysis showed that a gap was created near the edges of the slice; thus, a likely path for Cd loss is from the perimeter of the sample before the two pieces of glass fuse together, as shown in Figure 7.

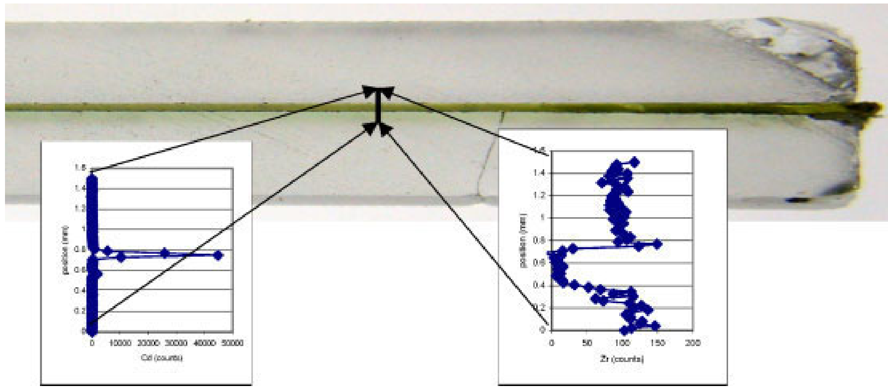


Figure 5. X-ray fluorescence microprobe analysis–vertical slice from unheated (control) sample; Cd and Zr counts

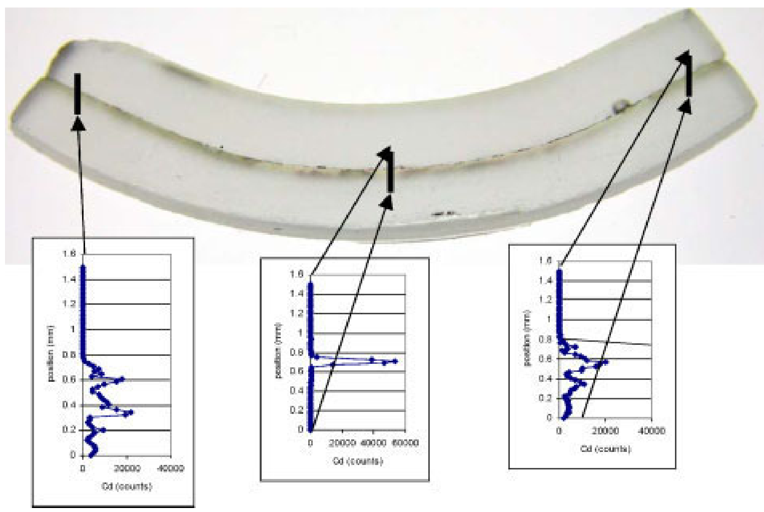


Figure 6. X-ray fluorescence microprobe analysis–vertical slice from middle of sample heated at 760°C; Cd counts in the center and the sides of the slice

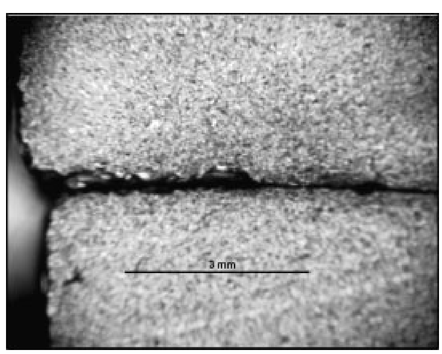


Figure 7. Microphotograph of the edge of a sample heated at 760°C for 30 min

Figure 8 show microprobe results, of a center section from the 1000°C sample and Figure 9 from a side section of the same sample. It is shown that Cd moved to considerable depths into the molten glass and 'froze' there after it cooled. The dispersion of Cd into the glass was more uniform in the side than in the middle of the sample. At the highest temperature we tried (1100°C) Cd diffused into greater depths around the junction

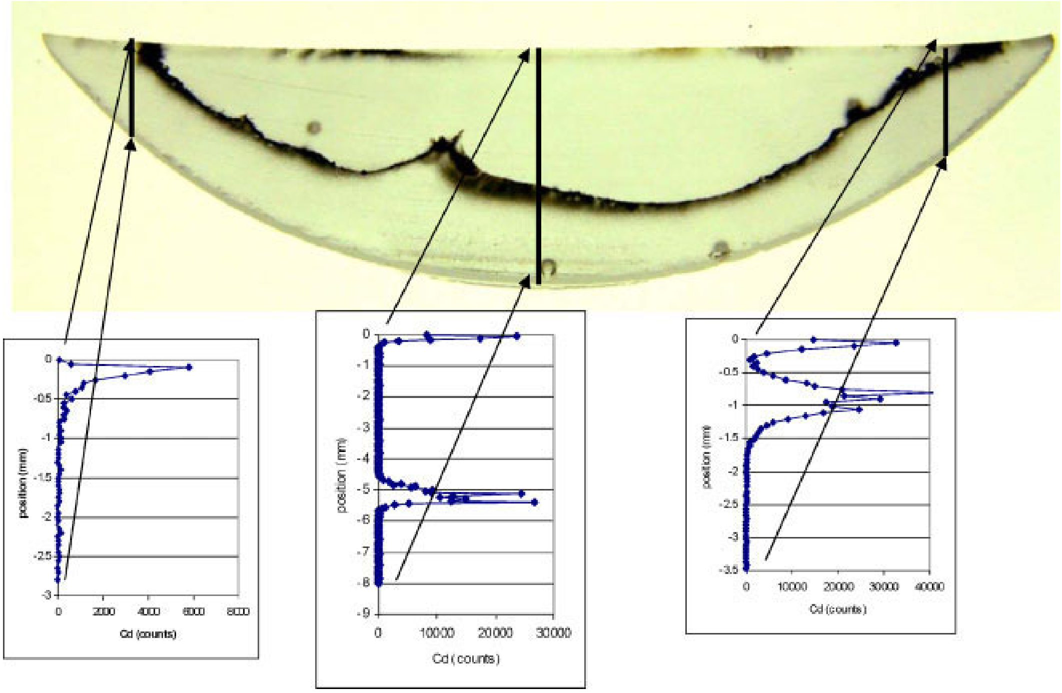


Figure 8. X-ray fluorescence microprobe analysis–vertical slice from middle of sample heated at 1000°C; Cd counts in the center and the sides of the slice

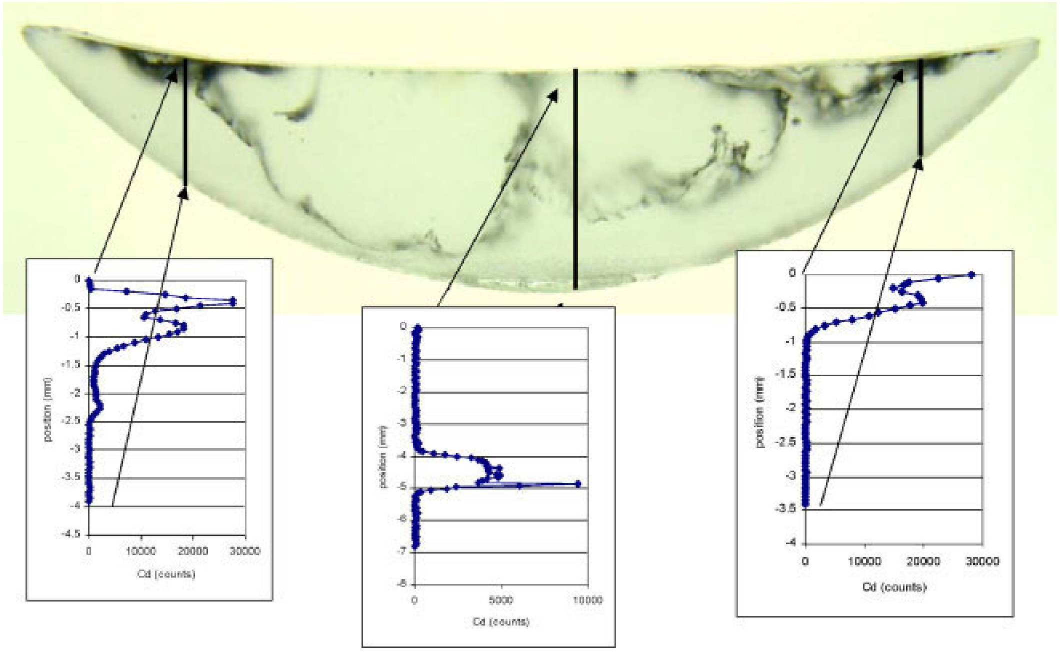


Figure 9. X-ray fluorescence microprobe analysis–vertical slice from side of sample heated at 1000°C; Cd counts in the center and the sides of the slice

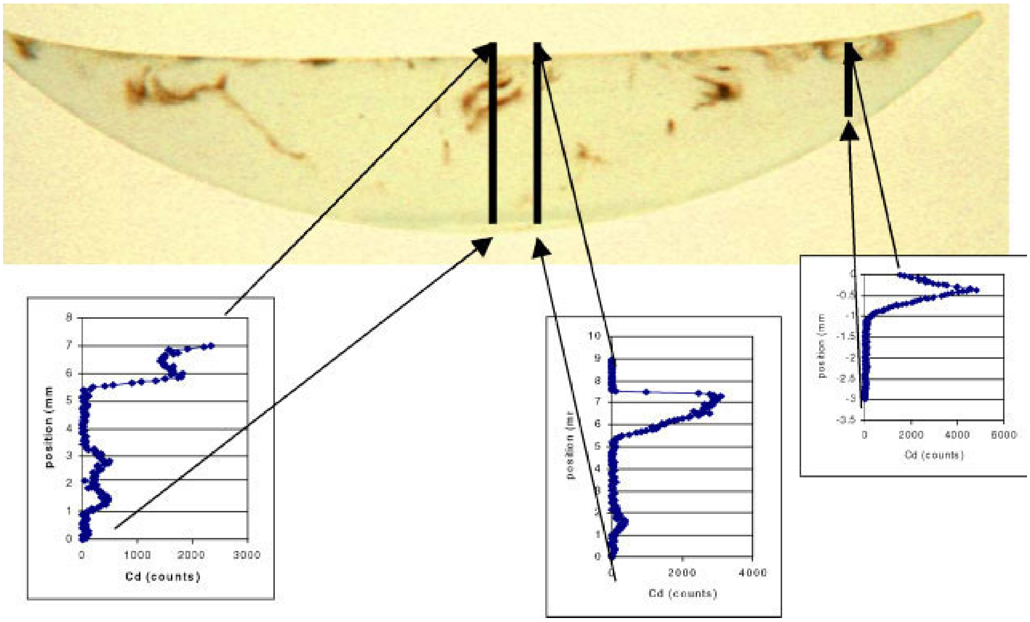


Figure 10. X-ray fluorescence microprobe analysis–vertical slice from middle of sample heated at 1100°C; Cd counts in the center and the sides of the slice

(Figure 10). Although higher temperatures produce greater Cd diffusion, the emissions analyses which show that the Cd loss was the same at all temperatures above 760°C indicate that Cd that has diffused into the glass does not enter the vapor phase in the temperature range of 760–1100°C.

5. ANALYSIS OF THE HEATED GLASS

We followed the standard ASTM C169-89 method[14] for chemical analysis of glass, involving fusion with lithium tetraborate and dissolution in HNO_3. The samples were ground to a fine powder and fused at 1100°C with lithium tetraborate powder (as flux). The fused material was poured into a 20% HNO_3 solution, which was kept at elevated temperature until the fused sample was completely disintegrated and dissolved into the solution. ICP analysis was performed on the solution for cadmium and tellurium. The results of this analysis are shown in Figure 11. The uncertainty of these results is much greater than that the uncertainty of the results presented in Section 3·2 for two reasons: (1) with the exception of the unheated (control) sample, only a small

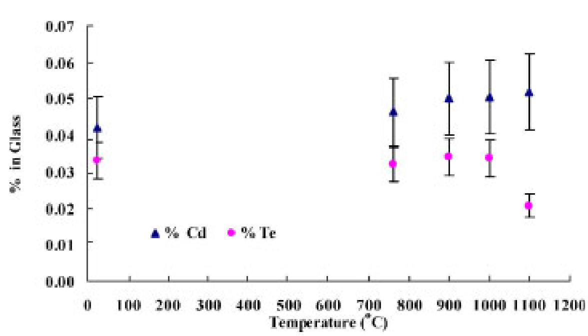


Figure 11. Cadmium and tellurium concentrations in unheated and in molten glass at different temperatures; average values and error bars showing % of error

part of the sample was ground and analyzed, and this may not represent the average concentration in the whole sample; and (2) the salts formed in solution increased the uncertainty of the ICP analysis to about 20% for Cd and 15% for Te.

These experiments showed that the Cd content in the unheated and the heated samples is the same (within the described level of analytical uncertainty), confirming the results of the emissions analysis that Cd was essentially retained in the glass during the heating experiments. The Te concentration in the heated glass, at 1100°C, was lower than the unheated sample, confirming the results of the air emissions analysis showing Te loss at high temperatures.

6. DISCUSSION

Pieces of CdTe PV modules of approximately 25×3 cm were heated to temperatures of 760–1100°C following standard UL and ASTM protocols. Four types of analyses were performed: (1) the thermogravimetric analysis showed weight loss of about 2%, which is equal to 77% of the weight of the EVA in the samples; (2) the Cd analyses (using inductively coupled plasma, ICP) showed that the total Cd emissions from each sample was about 3×10^{-4} g which corresponds to about 0·5% loss of the Cd content of the sample. The Te emissions were also very small at the typical residential flame temperatures of 700–900°C, but they were larger at higher temperatures (i.e., 1000–1100°C); (3) the synchrotron-based X-ray fluorescence microprobe analyses clearly show that Cd diffuses into the glass. Comparison of the Cd line scans in the center and the edges of each sample, together with microscopic analysis of the perimeter of the sample, show that the small Cd loss occurs from the edges of the PV module through the space of the two glass sheets before they fuse together. This loss is likely proportional to the ratio of the mass of cadmium (i.e., area of the sample) to its perimeter, and as such would be smaller in full modules. Our samples did not have 'edge delete', if the perimeter had a strip free of CdTe, Cd loss could have been even lower. On the other hand, the probability of a module being broken during a fire was not assessed; it is unlikely, however, that a large number of modules could be broken in pieces smaller than our samples; (4) pieces of heated samples were ground and fused with lithium tetraborate powder. The fused liquid was dissolved in HNO_3 and ICP analysis was performed for Cd and Te. The results of this analysis confirm that the Cd content remains constant, thus it is essentially retained into the glass matrix. The Te concentration in the burnt glass, at 1100°C, was lower than the unheated sample, confirming the results of the air emissions analysis showing Te loss at the high temperatures.

A possible explanation for the difference of the behavior of Cd and Te in the highest temperature experiments could be the difference in their oxidation states. Tellurium, when heated to high temperatures, likely oxidizes and subsequently vaporizes. On the other hand, cadmium oxide has a very low vapor pressure even at 1100°C (Figure 1). Additional studies are in progress to investigate the speciation of tellurium and cadmium in the glass matrix.

7. CONCLUSION

Heating experiments to simulate residential fires showed that most (i.e., 99·5%) of the cadmium content of CdTe PV modules was encapsulated in the molten glass matrix. This was confirmed with emissions chemical analysis, synchrotron-based X-ray fluorescence microprobe analysis and chemical analysis of the molten glass. Only $0{\cdot}5 \pm 0{\cdot}1\%$ of the Cd content of each sample was emitted during our tests that cover the wide flame temperature zone of 760–1100°C. The pathway for this loss was likely though the perimeter of the sample before the two sheets of glass fused together. In actual size PV modules, the ratio of perimeter to area is 13·5 times smaller than our sample; thus the actual Cd loss during fires will be extremely small (<0·04% of the Cd content). Multiplying this with the probability of occurrence for residential fires in wood-frame houses in the US (e.g., 10^{-4}), results in emissions of 0·06 mg/GW h (assuming 7 g Cd/m^2, 10% electric conversion efficiency and 1800 kwh/m^2/yr). As discussed in the introduction, the probability of sustained fires in utility systems must be much smaller, due to lack of combustible materials, and, therefore, emissions of cadmium during fires in central PV systems are considered to be essentially zero. The total cadmium emissions during the whole life-cycle of CdTe PV modules (ore mining, metal melting, purification, PV manufacturing) has been estimated to be about 20 mg/GW h.[15] These results apply to glass-to-glass CdTe PV modules which are the only ones in the market. Similarly to Cd, only a tiny percentage of Te was released in the typical residential fire temperature range 760–900°C, but a significant fraction was released at higher temperatures (1000–1100°C).

Acknowledgements

This work was supported by the Solar Technologies Program, Conservation and Renewable Energy, under Contract DE-AC02-76CH000016 with the US Department of Energy. The X26A beamline at the NSLS of Brookhaven National Laboratory is operated by a team of scientists from The University of Chicago's Consortium for Advanced Radiation Sources (CARS), the University of Georgia's Savannah River Ecology Laboratory (SREL), and Brookhaven National Laboratory's Environmental Sciences Department. Thanks are due to David Albin and Ramesh Dhere, NREL, Alan Fahrenbruch, Stanford University, and Tom Hansen, Tucson Electric, for sharing their data and observations, Ken Zweibel, NREL for being a guiding force behind this project, and First Solar, Ltd. for kindly providing pieces of their PV modules. This paper is an extended version of a poster paper entitled 'Experimental Investigation of Emissions and Redistribution of Elements in CdTe PV Modules During Fires' presented at the 19th European PV Solar Energy Conference and Exhibition, Paris, France, June 2004.

REFERENCES

1. Thumm W, Finke A, Neumeier B, Beck B, Kettrup A, Steinberg H, Moskowitz P. Environmental and health aspects of CIS-module production, use and disposal. *Presented at the 1st World Conference on Photovoltaic Energy Conversion*, Waikoloa, Hawaii, 5–9 December 1994.
2. Steinberger H. Health and environmental risks from the operation of CdTe and CIS thin film modules. *Presented at the 2nd World Conference on PV Solar Energy Conversion*, 6–10 July, 1998, Vienna, Austria.
3. UL1256 Standard: Fire test of Roof Deck Constructions, October 2002, Underwriters Laboratories Inc., Northbrook, IL.
4. ASTM E119-98, Fire Tests of Building Construction and Materials (UBC Standard No. 71), April 2001, American Society for Testing and Materials, West Conshohocken, PA.
5. Frisson L, Lieten K, *et al*. Recent improvements in industrial PV module recycling. *Presented at the 16th European PV Solar Energy Conference*, Glagow, UK, May 2000.
6. Mills K. *Thermodynamic Data for Inorganic Sulphides, Selenides and Tellurides*. Butterworth: London, 1974.
7. Korneeva I, Belyaev AV, Novoselova AV. *Zhur. Neorg. Khim.* 1960; **5**: 1.
8. Lorenz MR. *Journal of Physical Chemistry of Solids* 1962; **23**: 1449.
9. Goldfinger P, Jeunehomme N. *Transactions of the Faraday Society* 1963; **59**: 2851.
10. Brebrick RF, Strauss AJ. *Journal of Physical Chemistry of Solids* 1964; **25**: 1441.
11. Kubaschewski O, Alcockt CB. *Metallurgical Thermochemistry*, 5th edn. Pergamon: Oxford, 1979.
12. Yaws CL. *Handbook of Vapor Pressure*, *Volume 4*. Gulf: Houston, 1994–1995.
13. Drysdale D. *Introduction to Fire Dynamics*. Wiley; New York, 1985.
14. Standard Test Methods for Chemical Analysis of Sod-Lime and Borosilicate Glass, C 169-89, May 26, 1989, ASTM Committee on Standards, Philadelphia, PA.
15. Fthenakis VM. Life cycle impact analysis of cadmium in CdTe PV production, *Renewable and Sustainable Energy Reviews* 2004; **8**: 303–334.

Energy Policy 38 (2010) 5223–5228

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Cadmium flows and emissions from CdTe PV: future expectations

Marco Raugei [a,*], Vasilis Fthenakis [b]

[a] Environmental Management Research Group (GiGa), International Trade Business School (ESCI), Pompeu Fabra University, Barcelona 08003, Spain
[b] Brookhaven National Laboratory, Upton, NY 11973, USA, and Columbia University, New York, NY 10027, USA

ARTICLE INFO

Article history:
Received 5 October 2009
Accepted 4 May 2010
Available online 23 May 2010

Keywords:
Cadmium telluride photovoltaics
Cadmium
Prospective analysis

ABSTRACT

Cadmium telluride photovoltaic (CdTe PV) technology is growing rapidly, and already represents the largest contributor to non-silicon based photovoltaics worldwide. We assessed the extent to which CdTe PV will play a notable role in the Cd use and emission flows in the future, and whether it will be environmentally beneficial or detrimental. Our results show that while CdTe PV may account for a large percentage of future global Cd demand, its role in terms of Cd sequestration may be beneficial. We calculated that its potential contribution to yearly global Cd emissions to air and water may well be orders-of-magnitude lower than the respective current Cd emissions rates in Europe.

1. Introduction

Solar electricity is among the most promising forms of renewable energy. Thus, world photovoltaic (PV) production capacity, after having grown by about 40% a year for the best part of the last two decades, accelerated even more in 2006 and 2007. Estimates based on a survey of company statements and press releases from more than 200 companies worldwide indicate that this trend most likely will be maintained into the future, probably surpassing 40 GWp as early as 2012 (Jaeger-Waldau, 2008). Within the whole industry sector, cadmium telluride (CdTe) PV still is a comparatively new and minor player, and so far represents but a negligible fraction of the global demand for primary cadmium (approximately 0.6% in 2008). However, its market share is expanding very rapidly, already representing 5% of the total market for photovoltaics (EPIA and Greenpeace, 2008), with a single producer now supporting a production capacity of 1.1 GW/year (First Solar, 2009a).

Trends in worldwide use and production of cadmium long have caused concern, because of the metal's well-known toxicity; thus, the introduction to the market of a novel cadmium-based technology understandably generated mixed feelings in general public. Accordingly, we undertook a comprehensive prospective analysis to assess whether the often-voiced concern about the possible large-scale negative effects of Cd contamination from CdTe PV might be justified, and to what extent.

We began with a comprehensive review of the most recent information on current cadmium flows in Europe, giving us a reference frame within which to gauge the potential contribution of the possible future large-scale deployment of CdTe PV. The latter was evaluated from the life-cycle inventory (LCI) of current modules, including all related processes, from which we postulated three possible scenarios, based on an update of the results of the EU research project NEEDS (Frankl et al., 2008). We used two common reference time-horizons for drafting our prospective analyses: 2025 and 2050. The assumptions underlying the three scenarios are summarized as follows.

1. 'Pessimistic' scenario: this first scenario assumes that support for the current incentives to the PV sector will not continue long enough for the technology to become competitive with bulk electricity. Consequently, the growth of the whole PV sector is assumed to become stunted. We also considered that the relative market penetration of CdTe PV will remain very low until 2025, with moderate technological improvements that improve efficiency and reduce material demand per unit of output only happening in the last two-and-a-half decades (2025–2050).
2. 'Reference' scenario: PV market growth in this intermediate scenario essentially conforms to the latest predictions by the European PV industry association (EPIA and Greenpeace, 2008) till 2025, and is followed by a gradual reduction in the annual growth rate. CdTe PV is presumed to keep growing at a faster relative pace, reaching 45% of the total PV market by 2025, concurrent with large gains in efficiency and reduced material demand. By 2050, newer, 'third-generation' PV devices are assumed to have overtaken CdTe PV as a widespread alternative, capturing approximately one third of the market, and thus reducing the relative share of CdTe PV to approximately 35%.
3. 'Optimistic' scenario: in this last scenario, bolder annual growth rates are assumed for PV from as early as 2010, and

* Corresponding author. Tel.: +34 93 295 47 10, fax: +34 93 295 47 20.
E-mail address: marco.raugei@esci.es (M. Raugei).

0301-4215/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2010.05.007

the trend is expected to demonstrate quadratic growth through to 2050. The relative role of CdTe PV within the PV sector is assumed to be the same as in the reference scenario, except that in this scenario, we set an upper boundary of 1 TWp for the cumulative installed capacity of CdTe PV by 2050, to account for possible constraints in the supply of tellurium (Fthenakis, 2009).

In all three scenarios, we made the same conservative assumptions about the foreseeable increase in global Cd recycling rates, i.e. from the current 17.5–20% in 2025, and to 30% in 2050. Table 1 lists the specific assumptions on CdTe PV system efficiencies, lifetimes, and installed capacities.

2. Cadmium sources and uses

Cadmium occurs in small amounts in zinc ores, so that Zn producers do not have the option of not mining Cd. Zn extraction and processing have grown for the last three decades, from approximately 5.5 million tonnes per year in the early 1970s to about 11 million tonnes per year today (USGS, 2009a, 2009b). In contrast, total (primary+secondary) Cd demand expanded much more slowly in the 1970s and '80s, and since remained virtually stable at roughly 20,000 tonnes/year (USGS, 2009a, 2009c). In fact, since the global production of Zn has increased much faster than the corresponding demand for Cd, the annual amounts of raw Cd generated are entirely determined by Zn production rates.

We calculated that the global potential production of primary Cd from processing Zn ores was approximately 33,000 tonnes per year, based on an average Cd/Zn ratio in the ores of 0.003 (UNEP, 2006). This translates into a surplus of nearly 50% of primary Cd over the actual marketed amount; it is not accounted for officially, and remains stockpiled as an unrefined raw metal at zinc mining or refining sites, or is otherwise 'lost' to the environment. While these Cd stocks are not reported, nor even classifiable as actual emissions, the sheer lack of information on their management fuels concerns about their adverse environmental effects.

There are four principal industrial uses for cadmium: rechargeable (NiCd) batteries (82%), pigments (10%), plating (6%), and plastic stabilizers (1.5%) (UNEP, 2006; ICdA, 2005). In 2008, the new sector, CdTe PV, absorbed a quantity of Cd corresponding to about 0.6% of reported total Cd use in 2005. We underline here an important differentiation between batteries and PV on one side, and pigments, plating, and stabilizers on the other: while Cd is present in the former applications in self-enclosed compartments and can be fully recycled (at least in principle), the latter three applications are dissipative ones, and thus an inevitable source of eventual Cd contamination.

There is considerable uncertainty on the potential long-term change in global demand for NiCd batteries; however, it seems reasonable to assume that there should not be any major changes ahead in the next two–three decades compared to the last 10–15 years. Hence, for our prospective analysis, we decided to keep constant the current value of the yearly global Cd use for NiCd batteries. For all the other sectors analyzed, there is little reason to doubt that the present exponentially decreasing trend will be maintained, and we made our projections accordingly, employing regression equations.

We then integrated these extrapolated trends with our projections about the future development and deployment of CdTe PV according to the three scenarios discussed in Section 1 (Fig. 1). Depending on the assumptions, up to 15% of global Cd demand will be allocated to CdTe PV in 2050 (Table 1).

3. Cadmium emissions

The information on direct Cd emissions flows is fragmentary, and all inventories carry varying degrees of uncertainty. In our study, we collected the results of the two most relevant, up-to-date European research projects (ESPREME, 2006; ECB, 2007), and integrated them to encompass the full body of 27 countries constituting the European Union (EU-27).

By and large, the major source of yearly Cd emissions to air in Europe is the combustion of fossil fuels in coal- and oil-fired power plants and boilers, accounting for over 60% of the total. The average Cd content in coal reportedly ranges from 0.1 g/tonne (Pacyna and Pacyna, 2001) to 3 g/tonne (Swaine, 1995); petroleum oil has a comparatively lower Cd content, ranging 0.002–0.2 g/tonne (Karlsson et al., 2004). Other important sources of atmospheric Cd emissions are from producing and recycling galvanized iron and steel, as well as the life cycle of non-ferrous metal industrial products containing Zn, together adding up to approximately 15% of the total emissions. A third relevant source is the cement sector, contributing over 10% of the total. All other sectors, including the full life cycle of NiCd batteries (accounting for 82% of the total Cd demand) cumulatively add up to the remaining 15%.

The most pertinent sources of emissions to water again are the metal industries (71% of total), and the phosphate-fertilizer sector (approximately 20% of total), which is also principally responsible for the direct Cd pollution of agricultural soil. The sedimentary phosphate rocks from which virtually all the commercial phosphate is produced naturally contain cadmium

Table 1
Cd demand scenarios for CdTe PV in 2025 and 2050.

Year and scenario	CdTe PV module efficiency(%)	Cd Te PV module lifetime (years)	Cd demand for PV modules (g/kWp)[a]	Cumulative installed capacity (GWp)	Yearly primary Cd demand for CdTe PV (tonnes)	Percentage of yearly global primary Cd demand[b] (%)
2008 'Base year'	10.5	30	165	1.2	100	0.6
2025 'Pessimistic'	12.5	30	97	25	149	1.0
2025 'Reference'	13.5	30	90	195	1790	11
2025 'Optimistic'	14.5	30	84	260	2700	16
2050 'Pessimistic'	12.5	30	69	240	324	2.2
2050 'Reference'	14	30	62	820	1310	8.5
2050 'Optimistic'	16	35	54	1000	2440	15

[a] System installed capacity, assuming a performance ratio of 80%. Cd utilization rate is considered to remain at its current level. CdTe and CdS layer thicknesses for 2008, respectively, were assumed for current 'base year' modules, and reductions of 30% and 50% of these thicknesses, respectively, were assumed for 2025 and 2050 (the latter is a conservative estimate based on the information on past reductions in Cd use for module manufacturing, i.e. −30% from 2005 to 2008. Data provided by First Solar Inc. (2009)).

[b] Assuming constant primary Cd demand for NiCd batteries and diminishing demand for other sectors (pigments, plating, and plastic stabilizers).

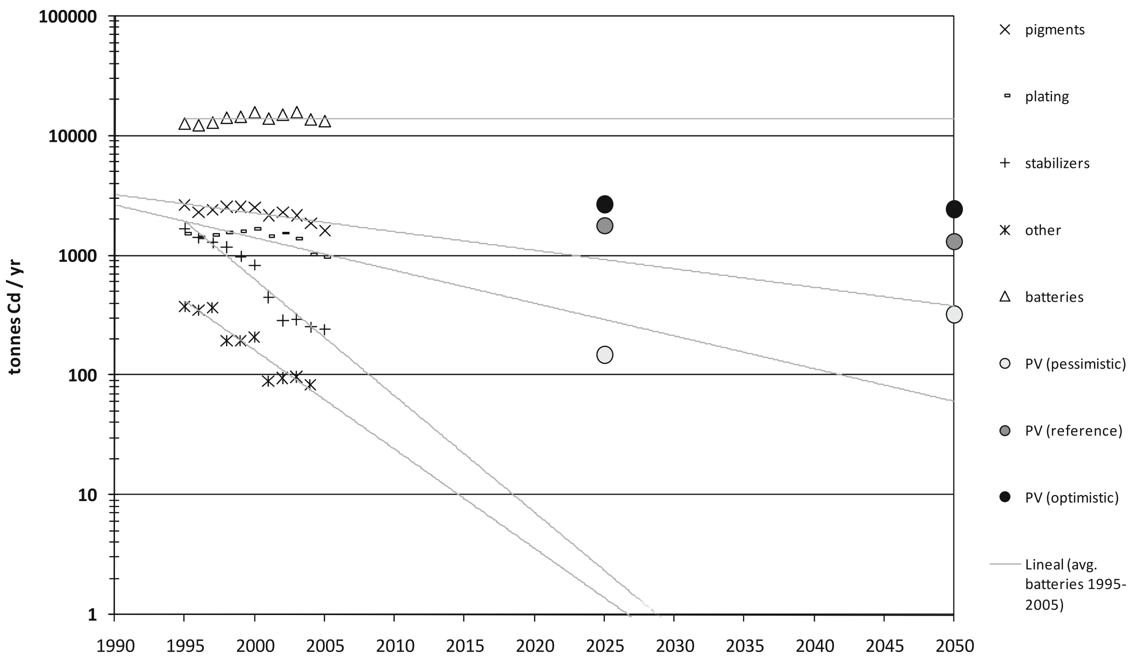


Fig. 1. Historical data and projections for world primary cadmium use by application, from 1990 to 2050 (logarithmic scale).

in concentrations from about 15 to over 200 mg (Cd)/kg (P_2O_5) (EC, 2001; Oosterhuis et al., 2000).

Fig. 2 summarizes this information in a flow-chart form, wherein the thicknesses of the arrows representing Cd-emission flows to water (5), soil (6) and air (7) are proportional to their corresponding magnitudes (tonne/year). The main conclusion from these findings is that the use of resources containing Cd as an impurity (i.e. fossil fuels and phosphorous oxides) and dissipative uses of the metal (e.g. alloys, pigments, and coatings) unquestionably are the greatest sources of life cycle Cd contamination. Public attention and policies first should be directed at curbing these to the maximum extent possible.

Combining the results of a life cycle study based on the current state-of-the-art of CdTe PV with these development scenarios, we then assessed the likely range of global emissions to air due to this technology up to 2050.

To track Cd emission flows, the life cycle of CdTe PV can be subdivided into four stages: (i) Cd extraction and refining, (ii) CdTe-powder production and PV-module manufacturing, (iii) PV-module use, and (iv) PV-module decommissioning. We also included the life cycle of balance of system (BOS) components in our analysis, assuming a typical modern power-plant scale installation (Mason et al., 2006).

(i) Cadmium production is driven entirely by Zn production; therefore, in accordance to the ISO standard 14044 (ISO, 2006), the emissions in the mining and Zn refining are entirely allocated to zinc. The emissions in all the steps following the formation of Cd sponge to the production of 99.999% pure Cd are allocated to the latter.

(ii) Cd emissions to air during Cd purification and CdTe production were estimated by Fthenakis (2004) to be 12 mg(Cd)/kg (Cd production). In the current vapor transport deposition-based manufacturing, the total Cd emissions from all manufacturing and recycling operations are 0.4 mg Cd/kg Cd input[1]. Including all the items in the life cycle inventory of PV-module manufacturing, we calculated here a total of 1.3 mg (Cd)/m^2 of module. It is noteworthy that by far the largest share of these emissions is unrelated to the specific PV technology being employed (e.g. tempered glass, EVA and the transparent conductive oxide (TCO) play a relevant role). BOS components contribute with an additional 0.4 mg (Cd)/m^2 (i.e. 25% of the total), which are mainly due to the steel for the support structure and the fuel used for construction. Water discharges are cleaned to below permissible limits (in Germany below 0.07 ppm) and there are no discharges to soil in the current CdTe PV manufacturing plants. The total Cd in liquid effluents is about 300 g/100 MW production[1], i.e. 0.3 mg (Cd)/m^2. According to the main source used for background data (Ecoinvent, 2007), an additional 0.8 mg (Cd)/m^2 are emitted to freshwater through the production of the TCO and tempered glass. Finally, BOS components add another 2.0 mg (Cd)/m^2 (i.e. 60% of the total), again mainly because of the steel structure.

(iii) Virtually no emissions are associated with the use phase, because cadmium in CdTe PV modules is present only as chemically stable compounds (i.e. CdTe and CdS) that are enclosed and sealed within two glass panes. Thus, we do not expect any emissions, while the modules are in place. Experimental tests showed that even in accidental fires, CdTe would be captured in the molten glass and very little could be released into the environment (Fthenakis et al., 2005).

(iv) For the disposal phase, we assumed that all the CdTe PV modules will be recycled at the end of their useful life (Fthenakis, 2009); BOS components were also assumed to be recycled for the most part, except for the concrete foundations, which were assumed to be left on site. No environmental credits were assigned for the materials sent to recycling (open-loop model). The current leading manufacturer (First Solar) implemented a take-back policy, setting aside sufficient funds to meet the estimated costs of collecting and recycling modules (First Solar, 2009b). Future competing manufacturers are likely to follow this example, and, indeed, this already has happened in at least two instances (PrimeStar Solar, 2009; Abound Solar, 2009). The recycling method, we analyzed in this study, is the only one that was tested on a full-production scale by the world's leading producer of CdTe modules (Sander et al., 2007);

[1] Data provided by First Solar Inc. (2009)

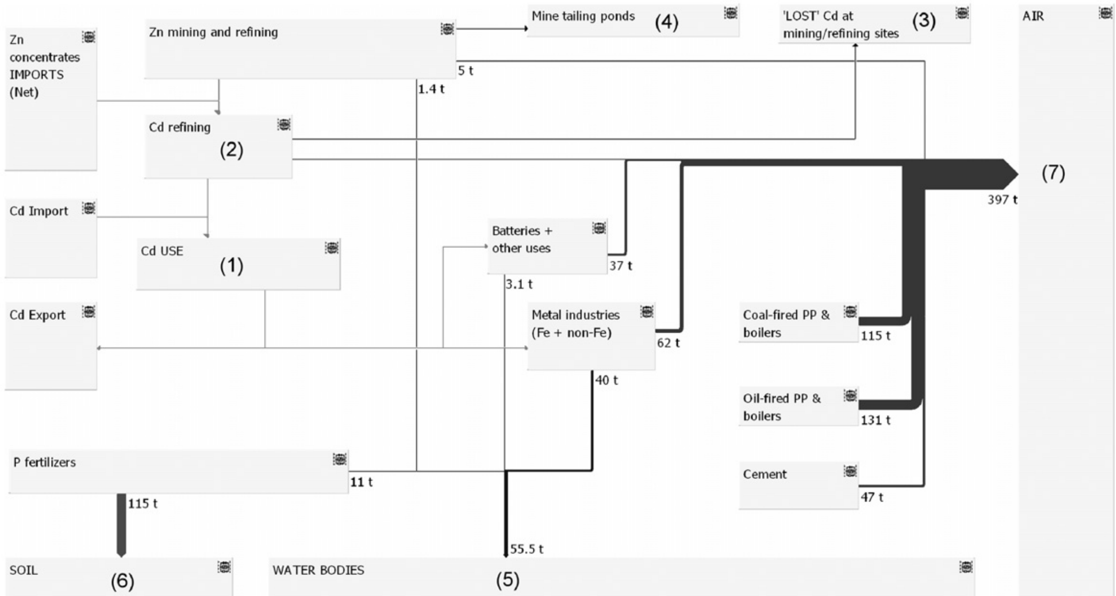


Fig. 2. Flowchart of current Cd flows in EU-27. Arrow thicknesses for all Cd-emission flows to water (5), soil (6), and air (7) are proportional to the corresponding magnitudes (tonne/year).

Table 2
Cd emission scenarios for CdTe PV in 2025 and 2050.

Year and scenario	Global Cd emissions to air due to CdTe PV (kg/year)	As relative to current Cd emissions to air in EU-27 (%)	Global Cd emissions to water due to CdTe PV (kg/year)	As relative to current Cd emissions to water in EU-27 (%)
2008 'Base year'	0.8	0.0002	2.0	0.004
2025 'Pessimistic'	17	0.0043	40	0.07
2025 'Reference'	130	0.033	310	0.56
2025 'Optimistic'	170	0.043	400	0.72
2050 'Pessimistic'	100	0.025	240	0.42
2050 'Reference'	320	0.080	760	1.4
2050 'Optimistic'	350	0.088	840	1.5

detailed inventory data were made available. The spent PV modules are cut and then crushed into pea-sized fragments, and leached in a dilute solution of sulphuric acid and hydrogen peroxide. Cd, Te, and Cu are precipitated from the solution together; the recovered filter cake finally is sent out for re-processing into high-purity metals. We omitted the re-processing of the filter cake from our analysis, adopting instead an open-loop recycling model according to which the Cd is attributed entirely to those other product systems that then use the purified metals (Guinée, 2001). The recycling processes employs 99.97% efficient HEPA filters throughout, so that Cd emissions to air from crushing operations are effectively captured. As mentioned above, the total residual emissions from all production and recycling operations are 0.4 mg Cd/kg Cd. We calculated Cd emissions to water by taking for granted that the treatment of the waste-water effluents assures they meet the current European limit of 0.2 ppm for cadmium (Council Directive 83/513/EEC); the resulting discharge rate is approximately 1 mg of Cd per square metre of decommissioned PV module. Actually, the currently operating facility in Frankfurt–Oder complies with an even lower threshold level (i.e. 0.07 ppm of Cd).

We then calculated the average yearly Cd emissions associated with CdTe PV in our three future scenarios by supposing that the modules' characteristics remain at their initial values up to the end of the time spans considered (i.e. 2008–2025 and 2026–2050), and discounting them per-kWp over the respective module lifetimes. All emissions are calculated on the basis of the full life cycle of the PV system, i.e. they include manufacturing and end of life of both the PV modules and BOS. Table 2 gives our results.

We note that these values can be regarded as the 'worst case' predictions for Cd emissions, since reasonably we can assume that changes in module characteristics will be gradual rather than abrupt, resulting in correspondingly better performance earlier (for instance, Cd use for module manufacturing in 2008 is already down by approximately 30% compared to 2005 levels). Also, a sizeable fraction of these Cd emissions are due to non-technology specific inputs (e.g. TCO and glass) and the steel-based support structure; both these contributions could be heavily reduced in the future, for instance switching to alternative encapsulation substrates and/or support materials (e.g. wood).

Fig. 3 presents a general overview of the current cadmium flows in the EU-27 (wherein items are numbered in the same way as in Fig. 2), and compares them to the findings from our prospective analysis of the potential global Cd emissions to air and water due to a large-scale deployment of CdTe PV in 2025 and 2050. Error bars are provided, indicating, respectively, +/−50% for EU flows, and the range of our three scenarios for the future global emissions due to CdTe PV.

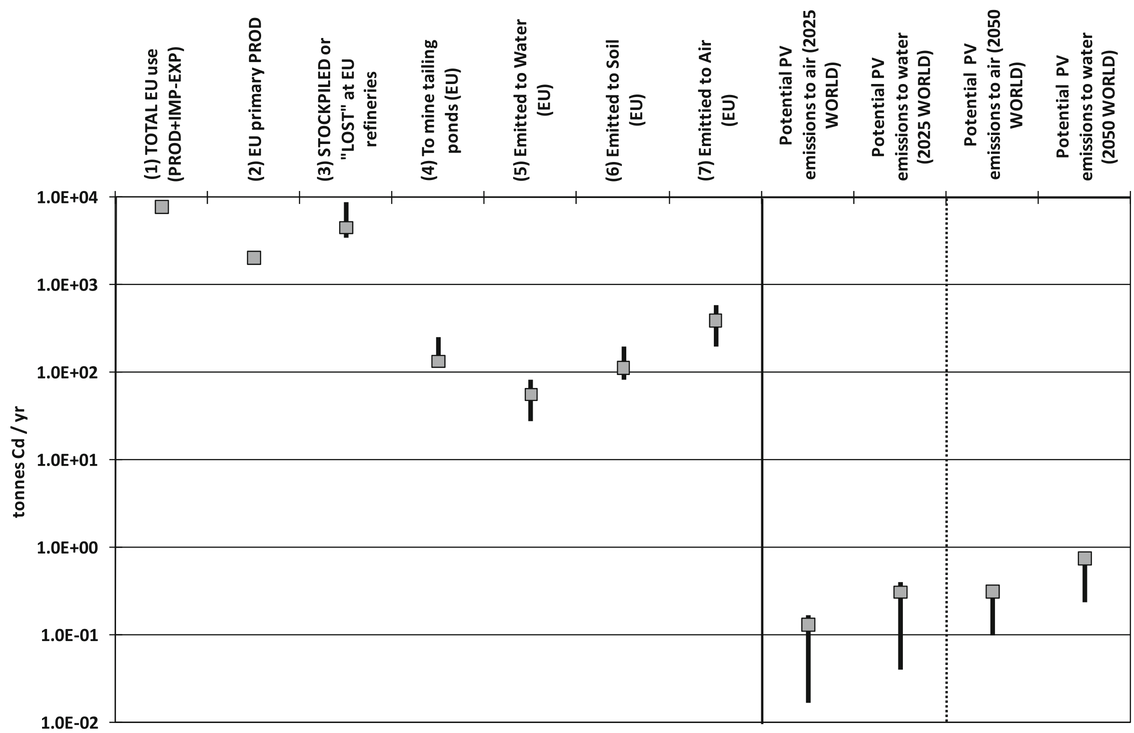


Fig. 3. Current Cd flows in EU-27 compared to potential future global Cd emissions caused by CdTe PV (logarithmic scale). Assumed maximum cumulative capacities are 260 GWp in 2025 and 1 TWp in 2050. Numbers in parenthesis (1–7) refer to corresponding flows in Fig. 2.

4. Discussion and conclusions

As is common in long-term prospective studies, an inevitable range of uncertainty remains, reflecting, on the one hand, the intrinsic variability in the life-cycle inventory databases, and on the other hand, the different assumptions made in the three scenarios. However, we are strikingly reassured after comparing the findings from our prospective *global* analysis to the current routine Cd flows in the EU-27.

Firstly, since cadmium is contained in zinc ores, is inevitably mined with them and generated as a by-product or a waste product of the Zn production, the increased usage of CdTe photovoltaics may be regarded as beneficial to the global environment by effectively sequestering a non-negligible amount of cadmium from otherwise potentially harmful left-over stockpiles.

Secondly, even under the largest growth scenario of 1 TWp of installed CdTe PV power in 2050, the related Cd emissions to water and air, would be lower by at least two and three orders-of-magnitude than the present yearly Cd emissions within the EU-27 alone. It is also noteworthy that whenever CdTe PV specifically replaces coal in power generation, it lowers by 100–360 times the associated Cd emissions to air (Fthenakis, 2004).

In conclusion, our prospective life cycle analysis suggests that a large growth in the CdTe PV sector has the potential to actually reduce, rather than increase, overall global cadmium-related environmental pollution.

Acknowledgement

The authors wish to thank First Solar for providing up-to-date material inventory and emissions information on the CdTe PV module manufacturing and recycling processes.

References

Abound Solar, 2009. 〈http://www.abound.com〉.

EC, 2001. Analysis and conclusions from Member States' assessment of the risk to health and the environment from cadmium in fertilizers—Environmental Resources Management (ERM), October 2001, Contract no. ETD/00/503201. 〈http://ec.europa.eu/enterprise/chemicals/legislation/fertilizers/cadmium/reports_en.htm〉.

ECB, 2007. European union risk assessment report: cadmium metal and cadmium oxide, final report. European Chemicals Bureau. 〈http://ecb.jrc.ec.europa.eu/existing-substances〉.

Ecoinvent (2007) Ecoinvent data v. 2.01. Swiss Centre for Life Cycle Inventories. 〈http://www.ecoinvent.ch〉.

EPIA, Greenpeace, 2008 Solar Generation V—solar electricity for over one billion people and two million jobs by 2020. European Photovoltaic Industry association. 〈http://www.epia.org〉.

ESPREME, 2006. Estimation of willingness-to-pay to reduce risks of exposure to heavy metals and cost–benefits analysis for reducing heavy metals occurrence in Europe, final activity report. 〈http://espreme.ier.unistuttgart.de〉.

First Solar, 2009a. Company Overview. http://www.firstsolar.com/pdf/FS_Company_FastFacts_MD-5-601-NA.pdf〉.

First Solar, 2009b. 〈http://www.firstsolar.com/recycle_modules.php〉.

Frankl P., Menichetti E., Raugei M., 2008. Final report on technical data, costs and life cycle inventories of PV applications, NEEDS deliverable 11.2—RS Ia. 〈http://www.needs-project.org〉.

Fthenakis, V., 2004. Life cycle impact analysis of cadmium in CdTe PV production. Renewable and Sustainable Energy Reviews 8, 303–334.

Fthenakis, V.M., Fuhrmann, M., Heiser, J., Lanzirotti, A., Fitts, J., Wang, W., 2005. Emissions and encapsulation of cadmium in CdTe PV modules during fires. Progress in Photovoltaics: Research and Applications 13, 1–11.

Fthenakis, V.M., 2009. Sustainability of photovoltaics: the case for thin-films. Renewable and Sustainable Energy Reviews 13 (9), 2746–2750.

Guinée, J. (Ed.), 2001. Life Cycle Assessment: An Operational Guide to the ISO Standards. Leiden University, Centre for Environmental Sciences.

ICdA, 2005. International Cadmium Association. 〈http://www.cadmium.org〉.

ISO, 2006. 14044—Environmental Management. Life Cycle Assessment. Requirements and Guidelines. International Organization for Standardization. 〈http://www.iso.org/iso/home.htm〉.

Jaeger-Waldau J., 2008. PV Status Report 2008—Research, Solar Cell Production and Market Implementation of Photovoltaics. European Commission Joint Research Centre Technical Notes. EUR_23604EN_2008. 〈http://sunbird.jrc.it/refsys/pdf/PV%20Report%202008.pdf〉.

Karlsson, S., Fredrikson, Holmberg, J., 2004. Future redistribution of cadmium to arable swedish soils: a substance stock analysis. Journal of Industrial Ecology 8 (4), 41–58.

Mason, J.M., Fthenakis, V.M., Hansen, T., Kim, H.C., 2006. Energy pay-back and life cycle CO2 emissions of the BOS in an optimized 3.5 MW PV installation. Progress in Photovoltaics: Research and Applications 14, 179–190.

Oosterhuis, F.H., Brouwer, F.M., Wijnants, H.J., 2000. A possible EU wide charge on cadmium in phosphate fertilizers: economic and environmental implications, Institute for Environmental Studies. Amsterdam, The Netherlands.

Pacyna, J., Pacyna, E., 2001. An assessment of global and regional emissions of trace metals to the atmosphere from anthropogenic sources worldwide. Environmental Reviews 9, 269–298.

PrimeStar Solar, 2009. ⟨http://www.primestarsolar.com⟩.

Sander K., Schilling S., Reinschmidt J., Wambach K., Schlenker S., Müller A., Springer J., Fouquet D., Jelitte A., Stryi-Hipp G., Chrometzka T. , 2007. Study on the development of a take back and recovery system for photovoltaic products. PVCYCLE association. ⟨http://www.pvcycle.org/fileadmin/pvcycle_docs/documents/publications/Report_PVCycle_Download_En.pdf⟩.

Swaine, D., 1995. Environmental Aspects of Trace Elements in Coal. Kluwer Academic Publishers, The Netherlands.

UNEP, 2006. Interim review of scientific information on cadmium. United Nations Environmental Programme. ⟨http://www.chem.unep.ch/Pb_and_CD/SR/Files/Interim_reviews/UNEP_Cadmium_review_Interim_Oct2006.pdf⟩.

USGS, 2009a, Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States. ⟨http://minerals.usgs.gov/ds/2005/140⟩.

USGS, 2009b, Minerals Yearbook—Zinc. United States Geological Survey. ⟨http://minerals.usgs.gov/minerals/pubs/commodity/zinc⟩.

USGS, 2009c, Minerals Yearbook—Cadmium. United States Geological Survey. ⟨http://minerals.usgs.gov/minerals/pubs/commodity/cadmium⟩.

Environmental Toxicology and Chemistry, Vol. 31, No. 7, pp. 1670–1675, 2012

Printed in the USA
DOI: 10.1002/etc.1865

FATE AND TRANSPORT EVALUATION OF POTENTIAL LEACHING RISKS FROM CADMIUM TELLURIDE PHOTOVOLTAICS

Parikhit Sinha,*† Robert Balas,‡ Lisa Krueger,† and Andreas Wade§
†First Solar, Tempe, Arizona, USA
‡Iris Environmental, Oakland, California, USA
§First Solar GmbH, Berlin, Germany

(*Submitted* 23 *November* 2011; *Returned for Revision* 17 *January* 2012; *Accepted* 8 *March* 2012)

Abstract—Fate and transport analysis has been performed to evaluate potential exposures to cadmium (Cd) from cadmium telluride (CdTe) photovoltaics (PV) for rainwater leaching from broken modules in a commercial building scenario. Leaching from broken modules is modeled using the worst-case scenario of total release of Cd, and residential screening levels are used to evaluate potential health impacts to on-site workers and off-site residents. A rooftop installation was considered rather than a ground-mount installation because rainwater runoff is concentrated via building downspouts in a rooftop installation rather than being dispersed across large areas in a ground-mount installation. Fate and transport of Cd from leachate to soil are modeled using equilibrium soil/soil-water partitioning. Subsequent migration to ambient air as windblown dust is evaluated with a screening Gaussian plume dispersion model, and migration to groundwater is evaluated with a dilution-attenuation factor approach. Exposure point concentrations in soil, air, and groundwater are one to six orders of magnitude below conservative (residential soil, residential air, drinking water) human health screening levels in both a California and southern Germany (Baden-Württemberg) exposure scenario. Potential exposures to Cd from rainwater leaching of broken modules in a commercial building scenario are highly unlikely to pose a potential health risk to on-site workers or off-site residents. Environ. Toxicol. Chem. 2012;31:1670–1675. © 2012 SETAC

Keywords—Cadmium telluride Leaching Risk assessment Fate and transport Cadmium telluride photovoltaics

INTRODUCTION

Solar energy is an important technology for climate change mitigation and development of a low carbon economy because it offers the highest global technical potential for electricity generation among renewable energy sources [1]. In particular, cadmium telluride (CdTe) thin film photovoltaic (PV) modules have the lowest life cycle carbon footprint and fastest energy payback time of current PV technologies [2]. Although CdTe has been shown to be significantly less toxic than elemental cadmium (Cd) on an acute basis [3], the primary health and safety concern for CdTe PV is the potential introduction of Cd compounds into the environment. When considered on a life cycle basis from raw material acquisition through product end-of-life, CdTe PV has been found to produce environmental Cd emissions to air that are no higher than those from conventional silicon PV technologies [4,5]. Moreover, because Cd is an unavoidable by-product of Zn mining, large-scale deployment of CdTe PV sequesters waste Cd that would otherwise be disposed of [6]. Prefunded end-of-life takeback and recycling programs also significantly reduce the overall environmental impact of CdTe PV modules [7].

Under normal operation, CdTe PV modules do not pose a threat to human health or the environment, because during the manufacturing process, the CdTe semiconductor layer is bound under high temperature to one sheet of glass, coated with an industrial laminate material, and then encapsulated between a second sheet of glass. However, some stakeholders have raised concerns about the potential exposure to CdTe from leaching of broken modules, defined as modules with cracked glass or broken pieces. Breakage results from extreme weather or human factors. Although rare, breakage followed by precipitation may potentially result in leaching of CdTe from modules and subsequent exposure to Cd compounds in soil, air, or groundwater. This analysis uses fate and transport modeling to estimate potential exposures to Cd compounds resulting from leaching and then evaluates the potential health effects associated with these exposures.

Fate and transport scenarios were evaluated for two geographic locations, southern Germany and California. Germany is among the world's leading PV markets, having accounted for nearly half of global demand in 2010 [8]. This analysis focuses on the higher solar irradiance region of southern Germany (Federal State of Baden-Württemberg). California is a leading PV market in the United States, and in 2011, the California state legislature adopted a renewable portfolio standard of 33% by 2020 (http://www.cpuc.ca.gov/PUC/energy/Renewables/index.htm).

In the present analysis, a commercial building scenario was chosen rather than a residential building scenario because the larger PV array size for commercial buildings increases the probability that module breakage may occur in a given year. However, both nonresidential (on-site) and residential (off-site) exposure scenarios were considered and evaluated using residential screening values. A rooftop installation was considered rather than a ground-mount installation because rainwater runoff can be concentrated via building downspouts in a rooftop installation (impact via concentrated stream) rather than being dispersed across large areas in a ground-mount installation. The evaluation considers the worst-case scenario in which the total mass of Cd in each broken module is released.

* To whom correspondence may be addressed (parikhit.sinha@firstsolar.com).
Published online 2 May 2012 in Wiley Online Library (wileyonlinelibrary.com).

MATERIALS AND METHODS

The present analysis considers broken CdTe PV modules located on the rooftop of a commercial building. Potential receptors considered for analysis include on-site commercial/industrial workers and off-site residents. Under this exposure scenario, potential exposure to Cd is considered for commercial/industrial workers via inhalation of, dermal contact with, and ingestion of Cd leached into soil, as well as exposure to groundwater potentially impacted by leachate. Also under this exposure scenario, potential exposure to Cd is considered for off-site residents via inhalation of windblown dust from affected soil and exposure to groundwater potentially impacted by leachate.

To characterize these potential exposure scenarios, exposure point concentrations of Cd in soil, air, and groundwater are estimated using a fate and transport analysis. The estimated exposure point concentrations are the relevant concentrations to which on-site workers or off-site residents may potentially be exposed. The exposure point concentration for soil is only relevant to the on-site worker who may potentially have incidental contact with on-site surface soil during the workday. The exposure point concentration for air is relevant to both the on-site worker and off-site resident who may potentially inhale affected ambient air. The exposure point concentration for groundwater is relevant to both the on-site worker and off-site resident who may potentially use groundwater as drinking water.

To evaluate potential human health impacts, estimated exposure point concentrations are compared to human health screening levels. Nonresidential screening levels are applicable to the on-site worker, whereas residential screening levels are applicable to the off-site resident. In this evaluation, the residential screening levels are used in comparison with estimated exposure point concentrations to be protective of both on-site workers and off-site residents. Specifically, for California, residential screening levels for soil (1.7 mg/kg) and air (1.4×10^{-3} μg/m^3) are used instead of commercial/industrial screening levels of 7.5 mg/kg and 6.8×10^{-3} μg/m^3, respectively. For Germany, a residential screening level for soil (2 mg/kg) is used instead of a commercial/industrial screening level of 60 mg/kg.

The fate and transport methodology used to estimate migration of Cd from the emission point (broken module) to the exposure point (soil, air, or groundwater) is summarized in Figure 1 and described with Equations 1 to 5 below. The concentration of Cd in leachate resulting from rainwater that falls upon and runs off broken modules is estimated based on a worst-case mass balance approach, where all the mass of Cd in each broken module is assumed to be transferred from the module into the volume of rainfall that falls upon the module during the exposure period. The subsequent concentration of Cd in rainwater runoff from the overall module array is calculated using a weighted average between impacted runoff from broken modules and nonimpacted runoff from unbroken modules. It should be noted that the assumption of total release of Cd from a broken module was adopted for the purpose of conducting screening level risk assessment, but is unlikely in the light of low experimentally measured emissions from broken or burnt modules [4].

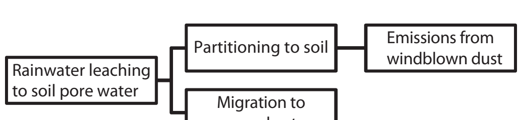


Fig. 1. Fate and transport schematic of migration from emission point (rainwater leaching from broken module) to exposure point in soil, air, and groundwater.

It is assumed that the rooftop runoff is conveyed via downspouts and discharged onto the ground surface over an area of 1 m^2 per downspout. Chemical concentrations in vadose (unsaturated) zone soil pore water at these discharge locations are assumed to be 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 nonimpacted. For the commercial building scenario, a roof with dimensions of 50×50 m is assumed to be completely covered by CdTe PV modules of dimensions 0.6×1.2 m each. Twenty-five downspouts are assumed for the building, based on the roof area being 25 times larger than a standard residential building (10×10 m) [9], where the latter would have one downspout.

The vadose zone soil pore water concentration in each 1 m^2 downspout ground surface area is estimated with the worst-case mass balance approach in Equation 1, where the numerator represents the total annual release of Cd and the denominator represents the total annual column of rainfall.

$$\mathrm{CV} = \frac{N \times M \times \mathrm{CF} \times B}{P \times A} \tag{1}$$

where CV is the Cd concentration in vadose soil pore water (mg/L); N is the number of modules (unitless); M is the mass of Cd per module (g); CF is the conversion factor (mg/g); B is the module breakage rate (year^{-1}); P is the annual average precipitation (L/m^2-year), which is annual precipitation (m/year) falling over 1 m^2 converted to units of L from m^3; and A is the area of roof-top array (m^2).

The potential transport of Cd to soil is evaluated in accordance with the equilibrium-partitioning approach described in the U.S. Environmental Protection Agency (U.S. EPA) soil screening guidance [10,11]. It is assumed that the surface soil where rainwater runoff is discharged is instantaneously impacted with Cd, at the concentration predicted by equilibrium partitioning between the water and soil matrices, as expressed by the soil/soil-water partitioning coefficient (K_d) value for Cd (Eqn. 2).

$$\mathrm{CS_{eq}} = \mathrm{CV} \times \left(K_\mathrm{d} + \frac{\theta_\mathrm{w}}{\rho_\mathrm{b}}\right) \tag{2}$$

where $\mathrm{CS_{eq}}$ is the equilibrium concentration of Cd in impacted soil (mg/kg); CV is the concentration of Cd in vadose zone soil pore water (mg/L); K_d is the soil/soil-water partitioning coefficient (L/kg); θ_w is the soil water-filled porosity (unitless); and ρ_b is the soil dry bulk density (kg/L).

For this scenario, it is assumed that the entire area of the site evaluated here is uncovered by concrete or asphalt and is open bare soil to allow the runoff water to penetrate into site soils. In actuality, commercial sites are often completely covered by concrete or asphalt. On-site commercial/industrial workers are assumed on average to be exposed to site soils across the entire portion of the site that is not occupied by the building. 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 nonimpacted soils (Eqn. 3). The exposure area (SA-A; Fig. 2) is assumed to be the same as that for a residential building [9], even though a commercial building property would likely be larger, therefore with larger

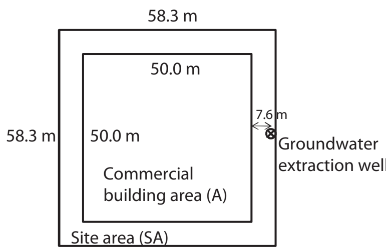


Fig. 2. Site schematic.

nonimpacted areas. This assumption accounts for the potential of at least part of the site to be covered.

$$CS = CS_{eq} \times \frac{IA}{(SA - A)} \quad (3)$$

where CS is the exposure point concentration of Cd in soil (mg/kg); CS_{eq} is the equilibrium concentration of Cd 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).

The potential transport of Cd from impacted soil to ambient air is estimated (Eqn. 4) using the U.S. EPA-recommended default windblown dust emissions flux for wind erosion (1.38×10^{-7} g/s-m^2) [11]. As noted above, the uncovered portion of the site is assumed to be bare earth for the purpose of this analysis, whereas commercial sites are frequently landscaped or covered by concrete or asphalt. It is assumed that Cd is present in this windblown dust at the soil concentration predicted by equilibrium partitioning (Eqn. 2). The U.S. EPA screening Gaussian plume dispersion model SCREEN3 [12] is used in conjunction with the emissions flux to estimate worst-case concentrations of dust and thus Cd in ambient air. The maximum hourly dust concentration from SCREEN3 was adjusted with a persistence factor of 0.08 [13] to derive the annual worst-case concentrations of dust.

$$CA = CS_{eq} \times CD \times CF_1 \times CF_2 \quad (4)$$

where CA is the exposure point concentration of Cd in air (μg/m^3); $CS_{eq}$is the equilibrium Cd concentration in soil (mg/kg); CD is the worst case dust concentration in air (mg/m^3); CF_1 is the conversion factor (kg/mg); and CF_2 is the conversion factor (μg/mg).

The potential transport of Cd to groundwater is evaluated in accordance with the dilution-attenuation factor (DAF) approach described in the U.S. EPA soil screening guidance [10,11]. It is assumed that vadose zone soil water, from the ground surface to the groundwater table, contains Cd at the module array-runoff concentration discussed above in Equation 1 (i.e., it is assumed the soil column does not adsorb any Cd). The potential concentration of Cd in groundwater at the hypothetical point of usage, which is assumed by the model to be a groundwater extraction well located 25 ft from the edge of the impacted area, is calculated by applying an upper bound (95th percentile) DAF [14] to the vadose soil water concentration (Eqn. 5). Note that for DAF values, higher percentiles represent numerically lower values, indicating less dilution-attenuation, and therefore higher groundwater concentrations.

$$CW = \frac{CV}{DAF} \times CF \quad (5)$$

where CW is the exposure point concentration of Cd in groundwater (μg/L); CV is the concentration of Cd in vadose zone soil pore water (mg/L); DAF is the dilution-attenuation factor (unitless); and CF is the conversion factor (μg/mg).

The specific fate and transport modeling parameters used in Equations 1 to 5 are summarized in Table 1. The parameters are the same for the two geographies evaluated, with the exception of higher average annual precipitation (37.32 inches/year; http://www2.lubw.baden-wuerttemberg.de/public/abt5/klimaatlas_bw/klima/aenderungen/ba-wue/niederschlag/index.html) for Baden-Württemberg, relative to California (21.44 inches/year; http://www.nationalatlas.gov/printable/precipitation.html). In addition, the German dry soil bulk density (1.4 kg/L; average between settlement and grassland areas [15]) is slightly lower than that used for California (1.5 kg/L [11]).

It should also be noted that the German Federal Environment Ministry does not provide a default value for the soil/soil-water partitioning coefficient data (K_d) for cadmium, due to low mobility in groundwater [16]. In this evaluation, the K_d value used for the California exposure scenario is applied to the southern Germany exposure scenario.

RESULTS

Exposure point concentrations of Cd in soil, air, and groundwater derived in Equations 3 to 5, respectively, are summarized in Table 2, and compared to human health screening levels for each of these media. For the California case, the screening levels in soil, air, and groundwater are from the California Human Health Screening Levels, U.S. EPA Region 9 Regional Screening Levels, and U.S. National Primary Drinking Water Regulations, respectively. Residential soil and indoor air screening values are used, both of which are more protective than the commercial building soil and outdoor air exposure scenarios considered here.

In the southern Germany case, the soil screening level is from the residential trigger value in Annex 2 of the Federal Soil Protection and Contaminated Sites Ordinance (http://www.umweltbundesamt.de/boden-und-altlasten/altlast/web1/berichte/pdf/bbodschv-engl.pdf). The standard residential trigger value in soil is 20 mg/kg, whereas for the special case of gardens in which children stay and food plants are grown, a residential trigger value of 2 mg/kg applies. Table 2 presents the latter more protective soil screening value, which is similar to the California Human Health Screening Levels value used for California. The German air screening level is based on World Health Organization air quality guidelines for Europe [17] and is slightly higher in magnitude than the California air screening level. The groundwater screening level is from the German regulation on drinking water (http://www.umweltbundesamt.de/wasser-e/themen/trinkwasser/gesetze.htm) and is the same as the U.S. drinking water standard.

In the California and southern Germany cases, exposure point concentrations in soil, air, and groundwater are one to six orders of magnitude below human health screening levels, indicating that it is highly unlikely that exposures to these media would pose potential health risks to on-site workers or off-site residents. In particular, air concentrations are below screening levels by five to six orders of magnitude, indicating exposure to ambient air is a de minimis exposure pathway.

For reference, the average background Cd concentration in California surface soils is 0.36 mg/kg [18], whereas average background surface soil Cd concentrations in Baden-Württemberg range from 0.2 to 0.3 mg/kg [19]. Therefore, modeled impacts to soil are over an order of magnitude below both human health screening levels and regional background levels.

Table 1. Fate and transport modeling parameters used in conjunction with Equations 1 to 5 for California (CA) and Baden-Württemberg (B-W) exposure scenarios[a]

Equation 1 parameters[b]	Equation 2 parameters[c]	Equation 3 parameters[d]	Equation 4 parameters[e]	Equation 5 parameters[f]
N: 3472	CV (CA/B-W): 0.00612/0.00352 mg/L	CS_{eq} (CA/B-W): 0.460/0.265 mg/kg	CS_{eq} (CA/B-W): 0.460/0.265 mg/kg	CV (CA/B-W): 0.00612/0.00352 mg/L
M: 6 g/module	K_d: 75 L/kg	IA: 25 m^2	CD: 5.5×10^{-6}	DAF: 7.82
CF: 1000 mg/g	θ_w: 0.3	SA: 3400 m^2	CF_1: 0.000001 kg/mg	CF: 1000 μg/mg
B: 0.04% $year^{-1}$	ρ_b (CA/B-W): 1.5/1.4 kg/L	A: 2500 m^2	CF_2: 1000 μg/mg	
P (CA/B-W)[g]: 545/947 L/m^2-year				
A: 2500 m^2				

[a] When two values are provided for a given parameter, first value is for CA and second value is for B-W.
[b] Parameters in Equation 1 are N (number of modules), M (mass of Cd per module), CF (conversion factor), B (module breakage rate), P (annual average precipitation), and A (area of building).
[c] Parameters in Equation 2 are CV (concentration of Cd in vadose zone soil pore water), K_d (soil/soil-water partitioning coefficient), θ_w (soil water-filled porosity), and ρ_b (soil dry bulk density).
[d] Parameters in Equation 3 are CS_{eq} (equilibrium concentration of Cd in impacted soil), IA (impacted area), SA (site area), and A (area of building).
[e] Parameters in Equation 4 are CS_{eq} (equilibrium Cd concentration in soil), CD (worst case dust concentration in air), CF_1 (conversion factor), and CF_2 (conversion factor).
[f] Parameters in Equation 5 are CV (concentration of Cd in vadose zone soil pore water), DAF (dilution-attenuation factor), and CF (conversion factor).
[g] Precipitation parameter (P) is based on annual average precipitation of 21.44 and 37.32 inches for California and Baden-Württemberg respectively.

For further perspective on soil impacts, Cd is commonly found in agricultural fertilizers. California is among the top users of agricultural fertilizer in the United States and analysis of metals in fertilizer samples has been performed by the California Department of Food and Agriculture, with median Cd concentrations of 89 mg/kg in phosphate fertilizer and 37 mg/kg in nitrogen/phosphorus/potassium (NPK) fertilizer [20]. Similarly, average Cd concentrations in phosphate and NPK fertilizer in Germany are 60 and 18 mg/kg, respectively (http://www.bfr.bund.de/cm/343/cadmiumaustrag_ueber_duengemittel.pdf). These values are over three orders of magnitude higher than the estimated exposure point concentration in soil in California and southern Germany (Table 2).

For reference, average background Cd (total suspended particulate) concentrations in California ambient air monitoring stations ranged from 0.0008 to 0.001 μg/m^3 in 2008 (http://www.epa.gov/air/data/geosel.html). Similarly, average background Cd concentrations in Europe range from 0.0001 to 0.0004 μg/m^3 in rural areas and 0.0002 to 0.0025 μg/m^3 in urban areas [21]. Therefore, modeled impacts to air are five orders of magnitude below both health screening levels and background levels.

For reference, the average background Cd concentration in groundwater from 1984 to 2004 in California Air Force bases ranged from <0.004 mg/L (50th percentile) to 0.006 mg/L (95th percentile; http://www.dtsc.ca.gov/assessingrisk/upload/metals_handout.pdf). In Baden-Württemberg, average background Cd concentrations in groundwater range from 0.00052 to 0.0039 mg/L [22]. Therefore, modeled impacts to groundwater in California and southern Germany are below both human health screening levels and background levels.

In addition to soil, air, and groundwater, another route of potential concern is direct discharge of rooftop runoff to stormwater catch basins. In combined sewer systems, stormwater and wastewater are collected together and treated at a publicly owned treatment works (POTW). The worst-case rooftop runoff Cd concentration (assuming total release of Cd from broken modules) is equivalent to the estimated Cd concentration in vadose soil pore water (CV; 0.004–0.006 mg/L; Table 1). Because this concentration is approximately consistent with drinking water standards, impacts to POTW's from rooftop runoff are expected to be minimal.

DISCUSSION

The fate and transport analysis conducted here represents a worst-case scenario of total Cd release from broken modules. An implicit assumption for this scenario is that a broken module would remain undetected and in the field over the exposure duration. This is a screening level assumption that would likely not occur given routine inspections of modules or power output monitoring. For example, the latter may include diagnostic comparison of actual to expected performance or comparison of co-located arrays to identify low performance areas and modules that are nonfunctioning potentially due to breakage.

Another implicit assumption is that emissions of CdTe from rainwater leaching of broken modules can be modeled as emissions of Cd, a "read-across" approach. This is a screening

Table 2. Estimated exposure point concentration (EPC) and corresponding human health screening level in soil, air, and groundwater.

	Soil EPC (mg/kg)	Soil screening level (mg/kg)	Air EPC (μg/m^3)	Air screening level (μg/m^3)	Ground-water EPC (mg/L)	Ground-water screening level (mg/L)
California[a]	1.28×10^{-2}	1.7	2.53×10^{-9}	1.4×10^{-3}	7.83×10^{-4}	5×10^{-3}
Baden-Württemberg[b]	7.35×10^{-3}	2	1.46×10^{-9}	5×10^{-3}	4.50×10^{-4}	5×10^{-3}

[a] California screening levels are from the California Human Health Screening Levels (http://www.calepa.ca.gov/brownfields/documents/2005/CHHSLsGuide.pdf) for soil, USEPA Region 9 (http://www.epa.gov/region9/superfund/prg/) for air, and U.S. National Primary Drinking Water Regulations (http://water.epa.gov/drink/contaminants/index.cfm) for groundwater.
[b] German screening levels are from Annex 2 of the Federal Soil Protection and Contaminated Sites Ordinance (http://www.umweltbundesamt.de/boden-und-altlasten/altlast/web1/berichte/pdf/bbodschv-engl.pdf) for soil, World Health Organization air quality guidelines for Europe [17] for air, and German regulation on drinking water (http://www.umweltbundesamt.de/wasser-e/themen/trinkwasser/gesetze.htm) for groundwater.

level assumption because CdTe is relatively insoluble [3,23]. For example, transformation and dissolution testing is designed to determine the rate and extent to which sparingly soluble metal compounds can produce soluble available ionic species in aqueous media under a set of standard laboratory conditions representative of those generally occurring in the environment. Based on long-term transformation and dissolution testing of CdTe, a 1 mg/L loading showed a concentration of 15 μg of Cd per L after 28 d, indicating approximately 1.5% solubility [24]. This is also consistent with the very low solubility product ($K_{sp} = 9.5 \times 10^{-35}$) for CdTe [25]. In addition to low solubility, CdTe can be contrasted with elemental Cd and other Cd compounds based on limited bioavailability and low acute toxicity, which result in an overall margin of safety of two orders of magnitude likely inherent to CdTe screening assessments developed using the read-across approach from Cd [25].

Because of the low solubility of CdTe, aggressive extraction methods are required to leach CdTe from a module. Such methods are used, for example, in the recycling process for CdTe modules. They involve crushing the module into mm-scale pieces and agitating it in an acidic solution [7]. These extraction methods in no way mimic actual broken or cracked module exposure to rainwater. Therefore, the assumption of total Cd release from broken modules is highly unlikely.

In addition to this worst-case assumption, other upper bound assumptions are used in the analysis. Migration from vadose zone soil pore water to soil is modeled with equilibrium partitioning, which represents the theoretical maximum concentration possible in the solid phase, for a given concentration in soil pore water. Subsequent migration from soil to air is modeled using the SCREEN3 U.S. EPA Gaussian plume dispersion model to estimate worst-case concentrations of windblown dust.

The approach used to estimate groundwater impacts is also upperbound because it does not account for the loss of chemical mass from the pore water during soil-water partitioning, instead assuming that the pore water is instantaneously in equilibrium with the solid soil phase. Accordingly, no mass in pore water is lost to the solid soil phase during partitioning, when in actuality some of this mass partitions into the solid soil phase, with a subsequent reduction in the concentration of Cd in the pore water with depth, until equilibrium is reached. Accounting for the loss of chemical mass from the pore water to the solid phase would lower chemical concentrations in soil water that are assumed to penetrate to groundwater and so reduce predicted groundwater exposures. In addition, the DAF assumes that there is an infinite source of mass available for release. Conserving mass would likely reduce the average long-term groundwater concentration estimated using the DAF approach and so result in lower groundwater exposures. Moreover, the dilution-attenuation factor used was a 95th percentile DAF where the higher percentiles represent numerically lower DAF values, indicating less dilution-attenuation and therefore higher groundwater concentrations. All of these factors contribute to the likelihood that impacts to groundwater are overestimated. Also as described earlier, under German groundwater assessment methodology, a default soil/soil-water partitioning coefficient data (K_d) is not provided, due to low mobility of Cd in groundwater [16] implying that using the DAF approach will result in an overestimate of groundwater concentration.

The soil/soil-water partitioning coefficient used in Equation 2 is pH-dependent. In the absence of site-specific soil pH, the default recommended soil pH of 6.8 was used in this analysis, corresponding to a Cd soil/soil-water partitioning coefficient of 75 L/kg. The latter coefficient ranges from 17 L/kg at soil pH of 5 to 4,300 L/kg at soil pH of 8 [11]. The equilibrium concentration of Cd in impacted soil is proportional to the soil/soil-water partitioning coefficient (Eqn. 2). Therefore, under acidic soils, the exposure point concentration in soil may be up to a factor of 4.4 lower than the concentration estimated in Table 2. For alkaline soils, the exposure point concentration in soil may be up to a factor of 57 higher than the concentration estimated in Table 2. However, because the soil exposure point concentrations in Table 2 are over two orders of magnitude below screening levels, potential health risks from exposure to soil are highly unlikely under varying soil pH.

The number of building downspouts (25) is based on the commercial building roof area being 25 times larger than a standard residential building with one downspout. The number of downspouts affects the impacted soil area (parameter IA in Eqn. 3), with each downspout discharging onto 1 m^2 of ground surface area. With additional downspouts, the soil exposure point concentration estimated with Equation 3 would increase proportionally. However, because the soil exposure point concentrations in Table 2 are over two orders of magnitude below screening levels, potential health risks from exposure to soil are highly unlikely under variations in the number of building downspouts.

Another screening level assumption is the module breakage rate. Product return statistics have been obtained in the 2011 fourth quarter from First Solar's warranty manager evaluating global warranty trends (J. Sokol, First Solar, Perrysburg, Ohio, USA, personal communication), including five years of actual performance data with extrapolations to later years of product life, based on an observed decline in breakage rate after the installation and initial operating period. Module breakage is rare, occurring in approximately 1% of modules over the 25-year warranty operating life, including the shipping and installation period. Of these breakages, over one-third occurs during shipping and installation and are removed for takeback and recycling. In addition, a proportion of broken modules have only chipped glass that does not affect the CdTe semiconductor layer. These two considerations considerably reduce the relevant breakage rate for modules that may be subject to leaching by rainfall. Nevertheless in this analysis, a conservative breakage rate of 1% over a 25-year life (0.04%/year) is applied.

The screening level approach used in this evaluation considers each exposure medium (soil, air, groundwater) separately. If an exposure point concentration for a chemical exceeds a screening level, the chemical is of potential concern to human health and requires further risk assessment. Conversely, if a screening level is not exceeded, it is highly unlikely that the chemical may pose a potential health risk in that exposure media. In addition to screening health risks for each exposure medium, cumulative risks across exposure media were considered using the exposure point concentrations in Table 2 in conjunction with U.S. EPA exposure assessment methodology [26,27] and the inhalation unit risk and oral reference dose for Cd (http://www.epa.gov/iris/subst/0141.htm). Across the exposure media of soil, air, and groundwater, cumulative risks and hazards are below one in one million and the hazard index of 1, respectively, as expected given that the media-specific exposure point concentrations are orders of magnitude below human health screening levels.

Overall, a worst case leaching scenario with screening level fate and transport modeling yields impacts to soil, air, and groundwater that are one to five orders of magnitude below human health screening levels in a California and southern

Germany exposure scenario. Potential exposures to Cd from rainwater leaching of broken modules in a commercial building scenario are highly unlikely to pose a potential health risk to on-site workers or off-site residents.

Acknowledgement—We wish to thank A. Uhlemann of the Berlin School of Economics and Law for contributing background environmental data regarding Baden-Württemberg, Germany, and J. McLaughlin of Iris Environmental for his insightful review.

REFERENCES

1. Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K. 2011. Special report on renewable energy sources and climate change mitigation: summary for policy makers. Intergovernmental Panel on Climate Change, Geneva, Switzerland.
2. de Wild-Scholten M. 2011. Environmental profile of PV mass production: globalization. *Proceedings*, 26th European Photovoltaic Solar Energy Conference, Hamburg, Germany, September 5-9, pp 3080–3083.
3. Zayed P, Philippe S. 2009. Acute oral and inhalation toxicities in rats with cadmium telluride. *Int J Toxicol* 28:259–265.
4. Fthenakis V. 2004. Life cycle impact analysis of cadmium in CdTe PV production. *Ren Sust Energy Rev* 8:303–334.
5. Fthenakis VM, Kim HC, Alsema E. 2008. Emissions from photovoltaic life cycles. *Env Sci Technol* 42:2168–2174.
6. Raugei M, Fthenakis V. 2010. Cadmium flows and emissions from CdTe PV: Future expectations. *Energy Policy* 38:5223–5228.
7. Held M. 2009. Life cycle assessment of CdTe module recycling. *Proceedings,* 24th European Photovoltaic Solar Energy Conference, Hamburg, Germany, September 21-25, pp 2370–2375.
8. Kann S. 2010. Global PV demand analysis and forecast. GTM Research, Boston, MA, USA.
9. California Environmental Protection Agency. 2005. Guidance for the evaluation and mitigation of subsurface vapor intrusion to indoor air. Interim final. Department of Toxic Substances and Control, Sacramento, CA, USA.
10. U.S. Environmental Protection Agency. 1996. Soil screening guidance: user's guide, 2nd ed. EPA/540/R-96/018. Office of Emergency and Remedial Response, Washington, DC.
11. U.S. Environmental Protection Agency. 2002. Supplemental guidance for developing soil screening levels for superfund sites. OSWER 9355. 4-24. Office of Solid Waste and Emergency Response, Washington, DC.
12. U.S. Environmental Protection Agency. 1995. *SCREEN3 model user's guide* EPA-454/B- 95-004. Office of Air Quality Planning and Standards, Research Triangle Park, NC.
13. U.S. Environmental Protection Agency. 1992. Screening procedures for estimating the air quality impact of stationary sources, revised. EPA-454/ R- 92-019. Office of Air and Radiation and Office of Air Quality Planning and Standards, Research Triangle Park, NC.
14. U.S. Environmental Protection Agency. 1996. Soil screening guidance technical background document, 2nded. EPA/540/R95/128. Office of Solid Waste and Emergency Response, Washington, DC.
15. Prinz B, Bachmann G. 1999. Ableitung niederschlagsbezogener werte zum schutz des bodens. In Bachman G, König W, Utermann J, eds, *Bodenschutz. Ergänzbares Handbuch der Maßnahmen und Empfehlungen für Schutz, Pflege und Sanierung von Böden, Landschaft und Grundwasser*, Vol 1, Section 5680. Erich Schmidt Verlag, Berlin, Germany.
16. Hudec B. 2003. Erfassung und bewertung von grundwasserkontaminationen durch punktuelle schadstoffquellen. Forschungsbericht 202 23 219. Bundesministeriums für Umwelt, Naturschutz, und Reaktorsicherheit, Berlin, Germany.
17. Theakston F. 2000. Air quality guidelines for Europe, 2nd ed. World Health Organization Regional Office for Europe, Copenhagen, Denmark.
18. Bradford GR, Change AC, Page AL, Bakhtar D, Frampton JA, Wright H. 1996. Background concentrations of trace and major elements in California soils. Division of Agriculture and Natural Resources, University of California, Riverside, CA, USA.
19. Bund-Länder-Arbeitsgemeinschaft Bodenschutz. 2003. Hintergrundwerte für anorganische und organische Stoffe in Böden. In Rosenkranz D, Bachmann G, König W, Einsele G, eds, *Bodenschutz*, 9006 39.Lfg XII/03: 1-51 und 40.Lfg III/04: A-1 - A-111. Erich Schmidt Verlag, Berlin, Germany,
20. U.S. Environmental Protection Agency. 1999. Background report on fertilizer use, contaminants and regulations. EPA/747/R98/003. Office of Pollution Prevention and Toxics, Washington, DC.
21. European Commission. 2000. Ambient air pollution by AS, CD and NI compounds, position paper, final version. Working Group on Arsenic, Cadmium and Nickel Compounds, Luxembourg, The Netherlands.
22. LUBW. 2011. Grundwasser-überwachungsprogramm. Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe, Germany.
23. Dean J. 1999. *Lange's Handbook of Chemistry*. McGraw-Hill, New York, NY, USA.
24. Brouwers T. 2010. Long term transformation/dissolution test of cadmium telluride. ECTX Consult, Liège, Belgium.
25. Kaczmar S. 2011. Evaluating the read-across approach on CdTe toxicity for CdTe photovoltaics. *Proceedings*, SETAC North America 32nd Annual Meeting, Boston, MA, USA, November 13-17, p 226.
26. U.S. Environmental Protection Agency. 1989. Risk assessment guidance for superfund volume I: human health evaluation manual (Part A). EPA/540/1-89/002. Interim final. Office of Emergency and Remedial Response, Washington, DC.
27. U.S. Environmental Protection Agency. 2009. Risk assessment guidance for superfund, volume I: human health evaluation manual (Part F, supplemental guidance for inhalation risk assessment). EPA-540-R-070-002. Final. Office of Superfund Remediation and Technology Innovation, Washington, DC.

Assessment of leaching tests for evaluating potential environmental impacts of PV module field breakage

Parikhit Sinha[1] and Andreas Wade[2]

[1]First Solar, Tempe, AZ, 85281, USA, [2]First Solar, Mainz, 55116, Germany

***Abstract* — Test methods from standard waste characterization leaching tests used in the U.S., Germany, and Japan were evaluated to determine if they can be used to help evaluate potential environmental impacts from PV field breakage. To assess the representativeness of leaching test methods, PV module breakage types were evaluated from warranty return data. Field breakages mainly consist of various types of stress and impact fractures in which modules remain largely intact with a number of glass fractures or cracks. By breaking modules into cm-scale pieces and tumbling them in solvent, waste characterization leaching tests can be more aggressive than PV field breakage conditions with regards to parameters such as fragment sample size, solvent, and treatment method. An alternative test method was previously used in Japan in which modules with a predetermined number of cracks were subjected to simulated rainwater. This approach is more representative of field conditions as modules are more likely to experience cracks under field conditions than to break into pieces.**

***Index Terms* —photovoltaic systems, environmental management, risk analysis**

I. Introduction

With global installed capacity reaching approximately 180 GW through 2014 [1], solar photovoltaics (PV) are making a significant contribution to new electricity supply in key markets around the world. By directly converting sunlight to electricity without emissions, solar PV can provide a sustainable alternative to conventional electricity generation. Development of utility-scale solar PV projects can require evaluation of a wide variety of potential environmental impacts, including impacts on biodiversity, land use, water resources, and human health [2][3]. Some stakeholders have raised concerns about the potential environmental impacts of PV modules due to the presence of environmentally sensitive materials, such as compounds of Pb, Cd, In, and Se. Under normal operation, PV modules do not pose a risk to human health or the environment, as the semiconductor layer is encapsulated between a layer of glass and a backsheet or a second layer of glass.

However, questions may arise with regards to non-routine events, namely broken modules subject to leaching by precipitation. Broken modules refer to modules with cracked glass or broken pieces which may result from extreme weather or human factors. In the case of thin film cadmium telluride (CdTe) PV modules, module breakage is rare, occurring in approximately 1% of modules over the 25-year warranty operating life (0.04%/yr) [4]. Of these breakages, over one-third occur during shipping and installation and are removed prior to plant operation. There is an observed decline in breakage rate after the installation and initial operating period (Fig. 1) [5]. In addition, a proportion of broken modules have only chipped glass that does not affect the semiconductor layer.

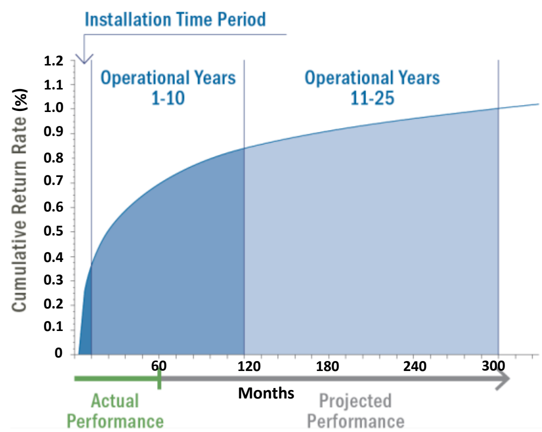


Fig. 1. Cumulative breakage rate as a function of months in service.

While rare, breakage followed by precipitation may potentially result in leaching of metals from modules and subsequent exposure in soil, air, or groundwater. Standard leaching tests could be used to try to evaluate the potential environmental impacts of broken PV modules. However, leaching tests have typically been designed for one of two objectives: identification of contents or waste characterization for landfill disposal.

Contents testing determines the total concentration of each target analyte in a sample. In the case of identifying metal constituents in PV modules, contents testing typically consists of acid digestion followed by spectrometry [6]. Samples are prepared by crushing module pieces to a powder (mm scale or smaller) and digesting with repeated additions of strong acid and oxidizing agent. The extracted metals are subsequently measured with methods such as inductively coupled plasma-atomic emission spectrometry. Waste characterization testing evaluates the soluble portion of analytes in a sample using conditions representative of a landfill. Test methods evaluate small (cm scale) fragments to account for potential crushing of waste by landfill equipment.

TABLE I
SUMMARY OF WASTE CHARACTERIZATION LEACHING TEST METHODS AND RESULTS FOR PV MODULES IN THE U.S., GERMANY, AND JAPAN

Geography		**United States [7]**	**Germany [8]**	**Japan [9]**
Leaching Test		U.S. EPA Method 1311 (TCLP)	DIN EN 12457-4:01-03	Ministry of Environment Notice 13/JIS K 0102:2013 method (JLT-13)
Sample size (cm)		1	1	0.5
Solvent		Sodium acetate/ acetic acid (pH 2.88 for alkaline waste; pH 4.93 for neutral to acidic waste)	Distilled water	Distilled water
Liquid:Solid Ratio		20:1	10:1	10:1
Treatment Method		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	20˚C	20˚C
Test Duration		18±2 hr	24 hr	6 hr
Leachate Cd Concentration (mg/L)	CdTe PV	0.22	0.0016 - 0.0040	0.10-0.13
	c-Si PV	Non-detect (<0.1)	-	Non-detect (<0.01)
	Limit	1	0.1	0.3
Leachate Pb Concentration (mg/L)	CdTe PV	Non-detect (<0.1)	-	Non-detect (<0.01)
	c-Si PV	3-11	-	Non-detect (<0.01) - 0.90
	Limit	5	-	0.3

The purpose of this study is to evaluate whether standard leaching tests can be used to help evaluate potential environmental impacts from PV field breakage. The focus is on waste characterization leaching tests, because contents testing provides data on the total quantity of metals but not their availability under field conditions. In this study, field breakage conditions are compared with waste characterization leaching test methods to determine the representativeness of the methods.

II. METHODS

Test methods from standard waste characterization leaching tests used in the U.S., Germany, and Japan were evaluated with regards to key parameters such as fragment sample size, solvent, and treatment method. To assess the representativeness of these parameters, product return data were obtained over nine years of field deployment of thin film CdTe PV modules. Module breakage types were analyzed, corresponding to standard categories recorded during warranty returns, including various types of stress and impact fractures. Data from the U.S. National Atmospheric Deposition Program were analyzed to assess the range of acidity typically present in rainfall, for comparison with solvents used in leaching tests.

III. RESULTS

Key test method parameters from leaching tests in the U.S., Germany, and Japan are presented in Table 1. These parameters are evaluated with regard to their relevance to PV field breakage conditions.

Sample size

The leaching test sample size in Table 1 ranges from 0.5-1 cm. In contrast, when PV modules break in the field, they tend to fracture (Fig. 2), rather than break into distinct pieces, due to the industrial laminate that encapsulates the module. Based on warranty return data over 9 years of service, field breakages largely consist of various types of stress and impact fractures (Fig. 3), not cm-scale fragments. Impact fractures are caused by external projectiles such as hail. Stress fractures are caused by dynamic/static loads such as wind, snow, and ice, or by thermal or physical propagation of undetected microscopic defects resulting from installation and handling damage. Module breakages can also occur at the attachment point due to improper clamping. Additional review of failure modes for PV modules is available from the International Energy Agency [10].

Fig. 2. PV module with fractured glass (impact, edge breakage).

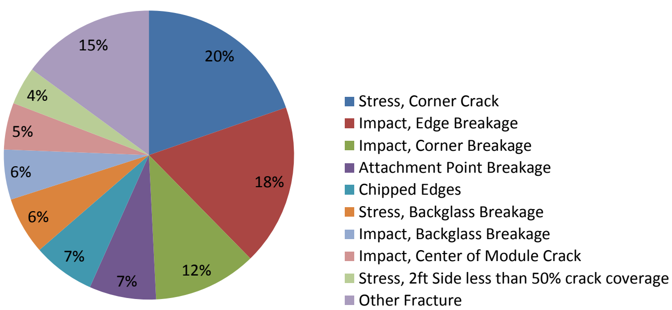


Fig. 3. PV module breakage types from warranty return data for modules put into operation (1-113 months in service).

Solvent

Solvents used in leaching tests range from organic acids to distilled water (Table 1). Organic acids are used to represent mixed waste disposal conditions in which organic acids are produced through fermentation of organic waste. Mixed waste conditions do not exist in PV field breakage. Based on data from the U.S. National Atmospheric Deposition Program [11], the average annual pH of rainwater in the U.S. ranges from approximately 4.7-6.7 (Fig. 4), which is less acidic than the range of 2.88-4.93 used in the TCLP test.

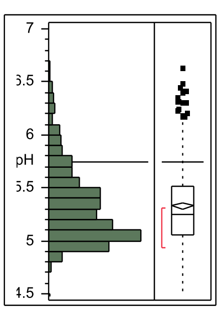


Fig. 4. Average annual rainfall pH in the U.S. (2011-2013) [11].

Treatment method

The sample treatment method of immersion in solvent and rapid end-over-end agitation (Table 1) is designed to accelerate the aging of the sample in order to allow a 6-24 hr test to represent long-term leaching potential in landfill conditions. However, there is an incentive to detect and remove non-performing modules, rather than leave them indefinitely in the field, which reduces the potential for long-term leaching. Broken modules can be detected though routine inspections of modules or power output monitoring. The latter may include diagnostic comparison of actual to expected performance or comparison of co-located arrays to identify low performance areas and modules that are nonfunctioning potentially due to breakage [4].

IV. Discussion

The evaluation of test methods indicates that waste characterization leaching tests can be more aggressive than PV field breakage conditions with regards to parameters such as fragment sample size, solvent, and treatment method. In order to provide further bounds on worst-case leaching potential from field breakage, data from two additional cases are also discussed. Data are presented from previous leaching tests of the raw semiconductor material CdTe, and from intentional crushing of PV modules by a heavy-duty landfill compactor.

CdTe has a very low solubility product in water (K_{sp} = 9.5×10^{-35}) derived using Outotec HSC Chemistry software (V. 7.0) and experimental water solubility testing following OECD Test Guideline 105 [12]. The CdTe K_{sp} corresponds to an equilibrium Cd concentration in water of 9.7×10^{-18} mol/L based on (1)-(3), or 1.1×10^{-12} mg/L given the molecular weight of Cd (112.414 g/mol). The stoichiometric balance in (2) is based on the high purity (99.999%) of semiconductor grade CdTe.

$$K_{sp} = [Cd^{2+}][Te^{2-}] \quad (1)$$

$$[Cd^{2+}] = [Te^{2-}] \quad (2)$$

$$[Cd^{2+}] = \sqrt{K_{sp}} \quad (3)$$

TABLE II
SUMMARY OF LEACHING TEST METHODS AND RESULTS ON THE RAW SEMICONDUCTOR MATERIAL CDTE*

	TCLP[a] [13]		WET[b] [13]		Dissolution [13]	Dissolution [14][15]	Bio-elution [14][16]
Sample size (μm)	63-125		63-125		63-125	92-262	74-<100
Solvent	Acetic acid, sodium hydroxide (pH 4.93)		Citric acid, sodium hydroxide (pH 5)		Hydrochloric acid, sodium hydroxide (pH 3.5)	CO_2-buffered water (pH 6)	Hydrochloric acid (pH 1.5)
Headspace	N_2	Ambient air	N_2	Ambient air	Ambient air	0.5% CO_2-in-air	Ambient air
Temperature (°C)	Room		Room		30	20-23	36-38
Treatment method	Agitation at 21 rpm for 18 hr		Agitation at 21 rpm for 48 hr		Agitation at 120 rpm for 72-600 hr	Agitation at 100 rpm for 168-672 hr	Agitation at 150 rpm for 1 hr, then resting for 1 hr
% Cd release (w/w)	0.58%	6.4%	0.56%	5.3%	≤3.6%	3.2 - 4.1%	2.3%

*See Discussion for interpretation for CdTe-containing devices
a – U.S. EPA Method 1311 Toxicity Characteristic Leaching Procedure
b - Waste Extraction Test

Given acidic conditions ranging from pH 1.5 to 6, leaching tests on the raw semiconductor material CdTe indicate a range of approximately 0.56% to 6.4% (w/w) solubility of Cd content in CdTe (Table 2). This range is nearly an order of magnitude lower than assumed in a previous worst-case environmental impact assessment [17], where the latter is based on modified availability testing that is more aggressive than standard waste characterization leaching tests and field breakage conditions.

Note that both the material tested and some of the test methods in Table 1 differ from those in Table 2. Table 1 provides leaching test methods and results for PV modules, whereas Table 2 provides leaching test methods and results for the raw semiconductor material (CdTe). Table 1 provides leaching test methods for waste characterization for landfill disposal. Table 2 provides leaching test methods for both waste characterization (TCLP and WET tests) and for evaluating solubility under a wider range of conditions (bioelution and long-term dissolution tests). The TCLP test is the federal U.S. waste characterization test whereas the WET test is the waste characterization test used in the State of California. For each of the TCLP and WET test methods in Table 2, two solubility results are provided corresponding to aerobic conditions (ambient air headspace) and anoxic conditions (N_2 headspace), with lower solubility observed under anoxic conditions.

Additional data is required to use the evaluation of the raw semiconductor material CdTe in Table 2 to try to understand potential leaching behavior of CdTe-containing devices. For example, CdTe PV modules contain approximately 6 g Cd content per 12 kg device [4] or 0.05% Cd content by mass, and the leaching potential is further limited by the monolithic glass-adhesive laminate-glass structure of the device that encapsulates the semiconductor material.

The potential leaching behavior of CdTe PV modules in a standard 1 L TCLP extraction fluid can be estimated using (4).

$$C_{Cd} = \frac{M_{EF} \times SL \times CO_{Cd} \times L_{Cd}}{AF_{EN} \times V_{EF}} \quad (4)$$

where,
C_{Cd}: TCLP Cd leachate concentration (mg/L),
M_{EF}: mass of extraction fluid (10^6 mg),
SL: TCLP solid-liquid ratio (1/20),
CO_{Cd}: Module Cd content (0.05%),
L_{Cd}: leaching potential of Cd content (6.4%),
AF_{EN}: adjustment factor to account for raw semiconductor material encapsulation in glass-adhesive laminate-glass structure, and
V_{EF}: volume of extraction fluid (1 L).

By taking the measured value of C_{Cd} from TCLP testing in Table 1 (0.22 mg/L), the adjustment factor (AF_{EN}) is estimated as ~7. In other words, in addition to the low mass concentration and solubility of the raw CdTe semiconductor material, the glass-adhesive laminate-glass encapsulation is estimated to further reduce solubility under standard TCLP conditions by nearly an order of magnitude, with the TCLP conditions already aggressive compared with field breakage.

In addition to the raw semiconductor material evaluation, a hypothetical case that provides perspective on field breakage is the intentional crushing of PV modules in a landfill. This is a hypothetical case because tractor compaction cannot take place in an operating PV array; however, even under six passes over the PV modules by a heavy-duty landfill compactor (Fig. 5), PV modules remain largely intact (Fig. 6) with the vast majority of pieces larger than the sample size

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JPHOTOV.2015.2479459

(0.5-1 cm) used in waste characterization leaching tests (Fig. 7) [18].

Fig. 5. Aljon model 91K compactor used to crush PV modules in a Municipal Solid Waste Landfill in the State of Arizona, USA.

Fig. 6. Compactor foot punch-out of a PV module crushed in a Municipal Solid Waste Landfill in the State of Arizona, USA.

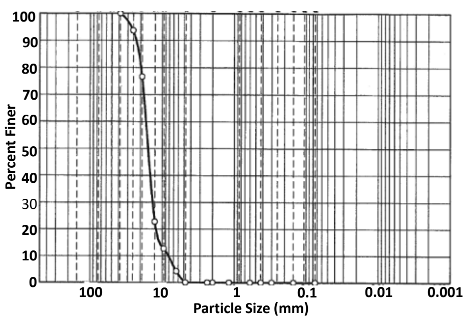


Fig. 7. Fragment size distribution of a PV module crushed in a Municipal Solid Waste Landfill in the State of Arizona, USA.

In testing of early generation PV modules, the New Energy and Industrial Technology Development Organization (NEDO) in Japan commissioned the study of leaching potential of thin film CdTe PV modules using methods more representative of field breakage conditions [19]. Instead of breaking modules into cm-scale pieces and tumbling in solvent, the testing subjected intact modules with 1 to 5 cracks to a quantity of simulated acid rain (pH 5) equivalent to 40 days of average rainfall. This approach is more representative of field conditions as modules are more likely to experience cracks under field conditions then to break into pieces.

Instead of developing leaching tests that more closely resemble field breakage conditions, some recent investigations have modified test parameters to be even more aggressive than standard waste characterization tests [20-22]. The use of finely ground samples and multiple extraction cycles in these investigations mimics the recycling process for PV modules [23] more closely than any environmental conditions, where the recycling process has the explicit objective to separate and then recover and reuse metals from end-of-life modules. As with contents testing, such worst case leaching tests provide data on the total quantity of metals but not their availability under realistic field conditions.

In addition, leaching tests are used to estimate potential chemical emissions; however, emissions are not equivalent to impacts. In order to conduct environmental impact analysis, fate and transport analysis is further needed to evaluate the chemical transformations and dispersion of chemicals in the environment in moving from the point of emissions to the point of exposure (or impact) [4]. Other factors such as breakage rate and exposure factors (frequency, type, and duration of exposure to impacted soil/water/air) also have to be accounted for to estimate potential impacts to human health and the environment.

V. Conclusion

Leaching tests used to evaluate the potential health and environmental impacts of rainwater leaching of broken PV modules need to reflect realistic PV field conditions. The evaluation of test methods indicates that waste characterization leaching tests can be more aggressive than PV field breakage conditions with regards to parameters such as sample size, solvent, and treatment method. Some recent worst case leaching tests are even more aggressive than waste characterization leaching tests and more closely resemble the PV recycling process or contents testing than realistic field conditions. An alternative test method was previously used in Japan in which modules with a predetermined number of cracks were subjected to simulated rainwater. This approach is more representative of field conditions as modules are more likely to experience cracks under field conditions then to break into pieces.

References

[1] International Energy Agency, "PVPS Annual Report 2014," Photovoltaic Power Systems Programme, Paris, France, 2015.

[2] R.R. Hernandez, S.B. Easter, M.L. Murphy-Mariscal, F.T. Maestre, M. Tavassoli, E.B. Allen, C.W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, and M.F. Allen, "Environmental impacts of utility-scale solar energy," *Renewable and Sustainable Energy Reviews*, Vol. 29, pp. 766–779, 2014.

[3] International Energy Agency Photovoltaic Power Systems Programme, *Energy from the Desert: Very Large Scale PV Power Plants for Shifting to Renewable Energy Future*, Report IEA-PVPS T8-01:2015, 2015.

[4] P. Sinha, R. Balas, L. Krueger, and A. Wade, "Fate and Transport Evaluation of Potential Leaching Risks from Cadmium Telluride Photovoltaics," *Environmental Toxicology and Chemistry*, Vol. 31, No. 7, pp. 1670–1675, 2012.
[5] First Solar, "Module Breakage Guidance," Application Note PD-5-350, 2014.
[6] International Electrotechnical Commission, "Electrotechnical products – Determination of levels of six regulated substances (lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, polybrominated diphenyl ethers)," IEC 62321, 2008.
[7] J. Bousselaire, "Analytical Report: Metals - TCLP," Test America, Irvine, CA, 2013.
[8] BAM Federal Institute for Materials Research and Testing, Test Report, Berlin, Germany, 2005.
[9] Ministry of Environment and Ministry of Economy Trade and Industry, "Reuse, recycle, and proper disposal of spent renewable energy equipment," Japan, 2014.
[10] International Energy Agency Photovoltaic Power Systems Programme, *Review of Failures of Photovoltaic Modules*, Report IEA-PVPS T13-01:2014, 2014.
[11] National Atmospheric Deposition Program, "National Trends Network - Seasonal Precipitation-Weighted Mean Concentrations," Illinois Water Survey, Champagne, IL, 2014.
[12] J. Liipo, "CdTe Water Solubility," Outotec Research, Pori, Finland, 2010.
[13] P. Sinha, "Cadmium telluride leaching behavior: Discussion of Zeng et al. (2015)," *J. Environ. Manage.*, Vol. 163, pp. 184-185, 2015.
[14] S. Kaczmar, "Evaluating the read-across approach on CdTe toxicity for CdTe photovoltaics," in *SETAC North America 32nd Annual Meeting*, 2011, p. 226.
[15] T. Brouwers, "Long term transformation/dissolution test of cadmium telluride," ECTX Consult, Liège, Belgium, 2010.
[16] T. Brouwers, "Bio-elution test on cadmium telluride," ECTX Consult, Liège, Belgium, 2010.
[17] V. Monier, and M. Hestin, "Study on Photovoltaic Panels supplementing the Impact Assessment for a recast of the WEEE Directive, FINAL REPORT," Bio Intelligence Service, 2011.
[18] K. A. Johnson, "Photovoltaic (PV) Solar Panel Experiment Results," Tetra Tech BAS, Phoenix, AZ, 2013.
[19] Central Research Institute for the Electric Power Industry, "Fiscal 1998 Report on the Results of Work Entrusted to the Renewable Energy and Industrial Technology Development Organization," Japan, 1999.
[20] Golder Associates, "Review and Comments on Reports by NGI: Environmental Risks Regarding the Use and Final Disposal of CdTe PV Modules and Leaching from CdTe PV Module Material – Results from Batch, Column, and Availability Tests," UK, 2010.
[21] PVThin, "Kommentar zum Abschlussbericht der Universität Stuttgart zum Untersuchungsvorhaben „Photovoltaik-Module – Umweltfreundlichkeit und Recyclingmöglichkeiten," Brussels, Belgium, 2012.
[22] PVThin, "Comment on Korean Research Report "Safety Assessment of Compound (CIGS, CdTe) Solar Module by Means of Environmental Effect Test and Analysis," Brussels, Belgium, 2013.
[23] M. Held, "Life Cycle Assessment of CdTe Module Recycling," in *24th EU PVSEC Conference*, 2009, pp. 2370-2375.

Science of the Total Environment 485–486 (2014) 319–328

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Future trends in soil cadmium concentration under current cadmium fluxes to European agricultural soils

L. Six, E. Smolders *

Department of Earth and Environmental Sciences, Division of Soil and Water Management, K.U. Leuven, Kasteelpark Arenberg 20, 3001 Heverlee, Belgium

HIGHLIGHTS

- The mass balance of cadmium in European agricultural soils was updated
- Lower-fertiliser use and lower cadmium deposition have lowered cadmium additions
- Cadmium concentrations in EU topsoils are predicted to decrease on the long term

ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 18 March 2014
Accepted 22 March 2014
Available online 14 April 2014

Editor: F.M. Tack

Keywords:
Cadmium
Fertilizer
Phosphate
Mass balance
Risk

ABSTRACT

The gradual increase of soil cadmium concentrations in European soils during the 20th century has prompted environmental legislation to limit soil cadmium (Cd) accumulation. Mass balances (input–output) reflecting the period 1980–1995 predicted larger Cd inputs via phosphate (P) fertilizers and atmospheric deposition than outputs via crop uptake and leaching. This study updates the Cd mass balance for the agricultural top soils of EU-27 + Norway (EU-27 + 1). Over the past 15 years, the use of P fertilizers in the EU-27 + 1 has decreased by 40%. The current mean atmospheric deposition of Cd in EU is 0.35 g Cd ha^{-1} yr^{-1}, this is strikingly smaller than values used in the previous EU mass balances (~3 g Cd ha^{-1} yr^{-1}). Leaching of Cd was estimated with most recent data of soil solution Cd concentrations in 151 soils, which cover the range of European soil properties. No significant time trends were found in the data of net applications of Cd via manure, compost, sludge and lime, all being small sources of Cd at a large scale. Modelling of the future long-term changes in soil Cd concentrations in agricultural top soils under cereal or potato culture predicts soil Cd concentrations to decrease by 15% over the next 100 years in an average scenario, with decreasing trends in some scenarios being more prevalent than increasing trends in other scenarios. These Cd balances have reverted from the general positive balances estimated 10 or more years ago. Uncertainty analysis suggests that leaching is the most uncertain relative to other fluxes.

1. Introduction

Cadmium (Cd) is a toxic trace metal that can be a risk for human health and the environment due to its environmental bioavailability and relatively large toxicity. Cadmium exposure to the general population occurs mainly via smoking, followed by ingestion of Cd containing food (IPCS, 1992). The risks due to Cd have been given much attention since the discovery of the '*itai-itai*' disease in Japan. The biological half-life of Cd in humans is 15–20 years. This means that a rare consumption of a high Cd containing food item has less effect than the lifetime exposure of moderately contaminated food.

Cadmium concentrations in crops increase with increasing soil Cd concentrations, all other factors being constant (Eriksson et al., 1996; McLaughlin et al., 2011; Smolders et al., 2007). Therefore, managing the risk of exposure to Cd via food includes managing the soil Cd balance and avoiding excessive accumulation of Cd in soils through additional inputs. Analysis of archived soil samples from experimental stations in UK, France and Denmark revealed that soil Cd increased by factors 1.3–2.6 during the 19th and 20th century (Jones et al., 1987; Juste and Tauzin, 1986; Rothbaum et al., 1986; Tjell and Christensen, 1985). Archived wheat grain samples similarly revealed an increasing trend in Cd concentrations over the same period in some field trials (Andersson and Bingefors, 1985; Jones and Johnston, 1989).

The atmospheric deposition of Cd and applications of phosphate (P) fertilizers, lime, sewage sludge or manure contaminated with Cd are net sources of Cd. These may exceed the leaching losses and removal of Cd with the harvested crop (crop offtake). Several mass balances for Cd have been used to derive trends in soil Cd in Europe. All predicted a net accumulation of soil Cd (Hellstrand and Landner, 1998; Hutton, 1983; Kiene, 1999; Moolenaar and Lexmond, 1998; Tjell and Christensen, 1992). The average soil Cd concentrations in European soils is about

* Corresponding author. Tel.: +32 16 32 96 77.
E-mail address: Erik.Smolders@ees.kuleuven.be (E. Smolders).

http://dx.doi.org/10.1016/j.scitotenv.2014.03.109

0.3 mg Cd kg^{-1}, equivalent to about 900 g Cd ha^{-1} in the plough layer (Smolders and Mertens, 2013). Between 1980 and 1995, the annual net input fluxes of Cd in European soils were estimated to range between 1 to 10 g Cd ha^{-1}, indicating that annual fluxes are much smaller than the total Cd stock in soils. In 2003, a proposal has been made in Europe to set limits on Cd in P fertilizers based on the stand-still principle, i.e. a proposal to set limits on Cd in fertilizers that would not lead to a long-term accumulation of Cd in European agricultural soils (CSTEE, 2002; DG Enterprise, 2003). That proposal has never been adopted into EU-wide regulations. Since that assessment in 2003, important emission controls have been taken to reduce atmospheric deposition of heavy metals to soils. Pacyna et al. (2009) concluded that the anthropogenic Cd emissions reduced considerably over the past 30 years. Next to a true reduction in Cd emission (and thus also Cd deposition), the current measurements of Cd concentration in precipitation with ICP-MS (inductively coupled plasma mass spectrometry) allows determination of lower Cd concentrations compared to previous methods (graphite furnace atomic absorption spectrometry or GF-AAS). Hence, the actual Cd deposition rates can now be estimated with greater accuracy compared to 1990s–2000s. In addition, trend analyses show a decreasing trend in P fertilizer consumption in Europe.

Leaching of Cd from soil is likely the most difficult flux to estimate in the mass balance since in situ annual flux data are not available at a large scale. Soil solution Cd concentrations can be estimated from solid-soil solution partitioning, expressed with a partitioning or distribution coefficient (K_D) of Cd in soils. This K_D value is most often related to basic soil properties (e.g. soil pH, organic carbon content, and total soil Cd concentration) (Groenenberg et al., 2010). By compiling different data sets with reliable K_D measurements, robust relationships can be deducted, which in turn allows a more reliable estimation of the Cd losses through leaching.

This study was set up to update the inventory of Cd inputs to agricultural soils in EU 27 + Norway (EU27 + 1) with recent data on atmospheric deposition, P fertilizers, sludge, lime and manure applications for soils used for arable production. The dietary intake of Cd mainly occurs via cereals and potatoes (Smolders and Mertens, 2013). Therefore, soils under cereal and potato production are used as cropping systems. The Cd output through leaching is estimated using an updated K_D model derived from coupled data on soil solution Cd concentrations and total soil Cd concentrations available from different studies. Model analysis is used to predict long-term (100 years) changes in Cd concentrations in top soils. In this study, the relative importance of the Cd inputs and outputs is estimated at European scale and compared with previous estimations. Expected long-term changes in soil Cd are estimated for the European average as well as for different regional scenarios representative for Europe. Finally, a sensitivity analysis is included.

2. The Cd mass balance: model description

The long-term changes in soil Cd concentrations were calculated from the annual input–output and the existing Cd concentration in European soils. The Cd concentration of the top soil at year i ($[Cd]_{soil,\ i}$, in mg Cd kg^{-1} soil) is calculated from the net Cd balance (i.e. input–output, in g Cd ha^{-1} yr^{-1}) in year (i − 1) and the total soil concentration in year (i − 1) ($[Cd]_{soil,\ i\ -\ 1}$, in mg Cd kg^{-1} soil):

$$[Cd]_{soil,i} = [Cd]_{soil,i-1} + \frac{input - output}{W_{soil}} \quad (1)$$

with W_{soil} as the soil weight in the plough layer (tonnes ha^{-1}). Using a bulk density of 1200 kg m^{-3} and a soil depth of 25 cm, this corresponds to $W_{soil} = 3000$ tonnes soil ha^{-1}. It was further assumed that the soil is homogeneously mixed without vertical variation of the soil properties in the top soil and that water transport is only in the vertical direction by prop flow. Preferential or bypass flow of water and thus Cd is not considered in this model. The impact of surface runoff and erosion was not considered as a loss of Cd, as erosion is merely a redistribution of Cd within the landscape.

This mass balance is made for the entire EU-27 + 1. For obtaining the EU average change, the EU average for the different parameters was used. Next to this, a full factorial analysis was performed, in which different model parameters (soil pH, % organic carbon, atmospheric deposition, P application, crop properties, leaching rate) are combined with each other. Although some combinations or scenarios are not equally important as others, this full factorial analysis allows quantifying the uncertainty on our estimated average. Furthermore, we have selected some regional (country) scenarios: Germany for Central Europe, United Kingdom for Western Europe, Spain for the Mediterranean region and Czech Republic for Eastern Europe.

The use of average balances, rather than local balances is preferred as the average situation controls the exposure of Cd to the general population. Cumulative lifetime consumption of staple crops, cereal and potato products is only exceptionally derived from a single location. The chronic (lifetime) Cd intake determines the risk of Cd for humans rather than the single high intake events (Järup et al., 1998; Smolders and Mertens, 2013). This justifies the use of generic mass balances instead of site-specific approach. Logically, a local mass balance is defensible when evaluating the likelihood that locally grown crops will exceed a food limit. Since a risk assessment is outside the scope here, we compare the current gross balances with similar balances made before for EU. In following sections the underlying assumptions of the model are explained in more detail.

2.1. Soil Cd concentrations of arable land in Europe

The soil Cd concentration at time t = 0 has a major impact on the predicted future Cd concentrations. Total soil Cd concentrations typically range between 0.1 and 1 mg Cd kg^{-1} (Smolders and Mertens, 2013). A large scale sampling programme by FOREGS in 2006, in which total metal concentrations are measured after a hot acid digestion, shows that the average Cd concentration in Europe is 0.28 mg Cd kg^{-1} with a standard deviation of about 0.24 mg Cd kg^{-1}. This is in close correspondence with country averages presented in the European risk assessment report (EU, 2007). For modelling the future soil Cd concentrations this average value, 0.28 mg Cd $(kg\ soil)^{-1}$, is used. For the country assessment, country specific data was used when available.

2.2. Atmospheric deposition

Cadmium is emitted to the atmosphere from anthropogenic and natural sources. The anthropogenic sources of Cd include industrial and small combustion, flue gas of industrial processes, waste incineration and others (EMEP, 2012). Emission trend analysis by Pacyna et al. (2007) shows that the highest emissions of Cd in Europe were around the mid-1960s when the production of non-ferrous metals (Zn smelters) was growing rapidly. Current Cd emissions are lower by a factor 5 since mid-1960s or by a factor 3 since 1985. From the mid-1970s on, the flue gasses were more filtered which resulted in a decline in Cd emissions.

Trace metals are included in EMEP's atmospheric monitoring programme since 1999, but earlier data have also been collected for a few sites. In 2010, a total of 33 sites are measuring trace metals in both air and precipitation in EU27 + 1 (EMEP, 2012). On these monitoring sites, two sampling methods are used, i.e. bulk collectors and wet-only collectors, although the wet-only collectors are being recommended in the EMEP manual. With wet-only collectors, the sampler is only opened during rain events. The main advantage of the wet-only collectors over the bulk collectors (always open) is that re-suspended Cd, which was first deposited elsewhere, is not accounted for in the measurements. After sampling, the concentrations are measured preferentially by the ICP-MS method which allows determination of Cd concentrations down to 0.01 μg Cd L^{-1}. Nevertheless, some countries still

Table 1
Atmospheric Cd deposition rates (g Cd ha^{-1} $year^{-1}$) in selected European countries (EU27 + 1) in 2010.

Country	Bulk sampler	Wet only collector
Belgium		0.2
Czech Republic	0.4	0.4
Denmark	0.2–0.8	
Estonia	0.5–1.2	
Finland	0.2–0.5	
France	0.3	0.1–0.2
Germany		0.2–0.3
Hungary		0.4
Latvia		0.4–0.6
Lithuania	0.4	
Netherlands		0.1–0.2
Poland		0.3–0.4
Slovakia		0.5–1.0
Slovenia	0.3	
Spain		0.3
Sweden		0.1–0.6
United Kingdom	0.1	
Norway	0.2–0.7	
EU-27 + 1 (mean and standard deviation)[a]	0.35 (0.21)	

Data is based on Cd measurements of the EMEP/CEIP monitoring sites.
[a] The range was averaged to obtain a country mean and means of all country means were then calculated.

use ICP-OES or even GF-AAS, which may yield at least tenfold larger detection limits. For each monitoring station, information is available for each rain event or for a fixed period. Based on the precipitation (mm) recorded and the Cd concentration in the rainwater (μg Cd L^{-1}) measured per rain event, the Cd deposition (mg Cd m^{-2}) can be calculated. By summing all rain events and converting to g Cd ha^{-1}, we obtained an estimate for total Cd deposition per monitoring station. The Cd deposition ranges between 0.1 and 1.0 g Cd ha^{-1} (Table 1), with an average of 0.35 g Cd ha^{-1} yr^{-1} and standard deviation of 0.21 g Cd ha^{-1} yr^{-1}. Next to the average deposition rate, the scenario of zero atmospheric deposition and a realistic worst case of 0.7 g Cd ha^{-1} yr^{-1} were also used in the full factorial analysis.

For comparison, total annual Cd emissions reported by EMEP and in the ESPREME project (espreme.ier.uni-stuttgart.de; EU 6th framework programme) divided by the total surface of Europe yield an average atmospheric deposition ranging between 0.2 and 0.6 g Cd ha^{-1} yr^{-1}, which is in close correspondence with measured Cd deposition.

The measured Cd deposition has decreased by a factor 5 or more in several monitoring stations, such as in Germany (EMEP/CEIP, 2012a). The Cd concentrations in mosses in Europe, indicating Cd deposition, decreased with a factor 1.3 to 4 depending on the country between 1990 and 2005 (Harmens et al., 2012). The previous Cd mass balances made for European soils (CSTEE, 2002; EU, 2007; Hutton and Symon, 1986; Jensen and Bro-Rasmussen, 1992; Nicholson et al., 2003) have assumed average Cd deposition fluxes that were up to 8 times larger than current means. The decreasing trends in measured Cd deposition (EMEP/CEIP, 2012b) are relatively more pronounced than the recent trends in estimated emissions (Pacyna et al., 2007; Pacyna et al., 2009). This is likely due to the lower detection limits with current analytical instruments (ICP-MS vs. GF-AAS) and due to the conversion of bulk samplers to wet only collectors.

2.3. Inputs from P fertilizers

Phosphate fertilizers, among all mineral fertilizers, are generally the major source of Cd in agricultural soils (Smolders and Mertens, 2013). The Cd input via fertilizers depends on the consumption of P fertilizers on one hand, and on the Cd:P_2O_5 ratio in the fertilizer. Detailed statistics on P fertilizer use (kg P_2O_5 ha^{-1}) in each EU 27 + 1 member state were provided by Fertilizers Europe (2011). The actual consumption is calculated by country experts, based on sales of fertilizers, the cropping area and the nutrient application rates for each crop. The current European average consumption of P_2O_5 on arable land is 22 kg P_2O_5 ha^{-1}, with an average P application of 21 kg P_2O_5 ha^{-1} for cereals and 45 kg P_2O_5 ha^{-1} for potato (Fertilizers Europe, 2011). The Cd concentration of P fertilizers (pure or blended) used in Europe were extensively investigated by Nziguheba and Smolders (2008). This study compiled the Cd concentrations of 196 samples of P fertilizer collected in Europe (EU-15). The Cd concentrations ranged from <0.1 to 120 mg Cd (kg P_2O_5)$^{-1}$, with a mean of 36 mg Cd (kg P_2O_5)$^{-1}$. Using this mean Cd concentration for P fertilizers, the annual input of Cd to arable soils is estimated to be about 0.8 g Cd ha^{-1} yr^{-1} for the European average consumption, also 0.8 g Cd ha^{-1} yr^{-1} for cereal-based production, 1.6 g ha^{-1} yr^{-1} for potato production and for potato (1 year)-cereal (2 years) rotations a Cd input of 1.1 g Cd ha^{-1} yr^{-1} is calculated. Country averages of Cd inputs to cereals through P fertilizers for different European scenarios are shown in Table 6.

Since 1980, the consumption of P fertilizers in Europe (EU27 + 1) has decreased by a factor four (Fig. 1). The actual Cd input via fertilizers has decreased mostly due to the reduction in P fertilizers use. For example, at the average use for arable land of 36 kg P_2O_5 ha^{-1} in 2001, the Cd input was 1.3 g Cd ha^{-1} yr^{-1}. Previous Cd mass balances estimated Cd addition rates via fertilizers between 0.5 and 4.4 g Cd ha^{-1} yr^{-1} (Alloway and Steinnes, 1999; CSTEE, 2002; Hutton, 1983; Moolenaar and Lexmond, 1998; Nicholson et al., 2003). These larger estimates most likely reflect the larger use of P fertilizers in Europe 10 to 30 years ago (Table 7).

2.4. Inputs from manure, sludge and lime

Inputs from manure, sludge and lime are in general difficult to estimate since national statistics are limited in Europe.

The Cd application through manure ranges between 1.4 and 6.1 g Cd ha^{-1} yr^{-1}, when applied at an equivalent N rate of 250 kg N ha^{-1} yr^{-1} (Nicholson et al., 2003). Such high estimate is unlikely representing the average EU scenario, since manure is only locally the single N source to plants. More importantly, this major local source of Cd is not an important net source of Cd at large scale. A majority of Cd in manure is derived from animal feed that is produced in the same region. Hence, manure application recycles Cd that was previously taken by crops (see crop offtake). Logically, at field scale, net accumulations of Cd are possible where manure is applied, whilst net depletion is possible where the feed is produced. For these reasons, average Cd mass balances only consider the net input of Cd through manures as the Cd that comes from imported animal feed (Moolenaar and Lexmond, 1998).

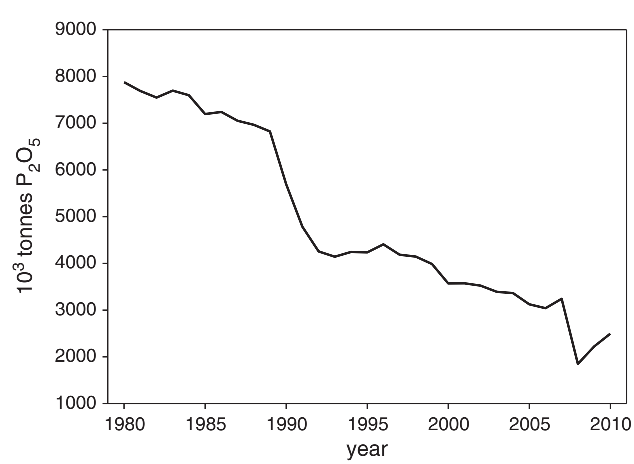


Fig. 1. Evolution of mineral P fertilizer consumption (10^3 tonnes P_2O_5) in the EU-27 member states + Norway from 1980 to 2010.
Source: IFA DATA (2012).

We assume that cereals are the main constituent for animal feed and we used typical grain Cd concentrations for calculations (Eriksson et al., 1996). We further assume that the resulting manure is evenly spread over the arable land in Europe (i.e. approximately 103×10^6 ha). In theory, Cd export via agricultural products (meat, milk, etc.) should also be subtracted, but that refinement was not done since the Cd input via manure is already a marginal one. Cereal grains contain on average 0.02 to 0.05 mg Cd (kg grain)$^{-1}$ (Smolders et al., 2007). In 2010, about 30×10^6 tonnes animal feed were imported into Europe. Based on these animal feed imports to EU-27, an annual Cd input of about 0.006–0.014 g Cd ha^{-1} yr^{-1} was estimated, yielding 0.01 g Cd ha^{-1} yr^{-1} for the European average in this assessment.

Hellstrand and Landner (1998) estimated that a total of 155 kg Cd is imported into Sweden through animal feeds. This corresponds to a Cd flux of 0.05 g Cd ha^{-1} yr^{-1} at the national level. The same Cd flux via manure was estimated by Moolenaar and Lexmond (1998) for Dutch mixed farming systems. In a recent mass balance study conducted for Sweden by Sternbeck et al. (2011), it was concluded that manure is of little importance for the accumulation of Cd in soil and was therefore not considered in their assessment.

For estimating Cd input through sludge application, Nicholson et al. (2003) based their calculations on N-requirements. If 250 kg N ha^{-1} is applied as sludge, this would lead to a Cd input of 19 g Cd ha^{-1} yr^{-1} with sludge containing 3.4 mg Cd (kg dry basis)$^{-1}$. Currently, the estimated EU average Cd content of sewage sludge is 1.8 mg Cd (kg dry basis)$^{-1}$, which leads to a twofold reduction compared to Nicholson et al. (2003). As with manure, such values unlikely represent the average situation, since such large amounts are only applied locally. Additionally, the application of sewage sludge to agricultural land is regulated differently among European Member States.

For above reasons, total Cd inputs to arable land via sludge application were calculated from the amounts of sludge used for agriculture (i.e. about 40% of total sludge production (Milieu et al., 2008)) and the average Cd concentration of the sludge produced in Europe (Table 2). Again it was assumed that all sludge is evenly spread over the arable land in EU 27 + 1 (i.e. 103×10^6 ha). Obviously, this results in an underestimation of local application rates, which can lead to locally high concentrations of Cd. The sludge application rates for some EU 27 + 1 countries and the Cd concentration of sludge used for fertilizer purposes are represented in Table 2.

On average, again assuming all sludge is evenly spread over arable land, the Cd inputs through sludge application are 0.05 g Cd ha^{-1} yr^{-1}. According to the country risk assessment studies submitted to the European Commission in 2000, country average fluxes were approximately 0.05 g Cd ha^{-1} yr^{-1} for Austria, Denmark, Belgium and Finland and were larger for The Netherlands and Germany: 0.2 g Cd ha^{-1} yr^{-1}.

In conclusion, sludge and manure application can be significant sources of Cd at a field level, but are no significant sources compared to fertilizer and atmospheric deposition inputs at the country or regional level (Table 6) with which the average trend of soil Cd should be calculated (de Meeûs et al., 2002). However, high application of sludge and/or manure could be a considerable input at parcel level and cause an increase in soil Cd concentrations. Local mass balances are therefore defensible when evaluating the likelihood that locally grown crops will exceed a food limit.

Only limited national data on application rates of lime and their Cd concentrations were found. We estimated the Cd input from liming using a Swedish risk assessment report (Sternbeck et al., 2011). Lime application rates of 100–150 kg CaO ha^{-1} yr^{-1} are recommended in Scandinavian countries to maintain pH at a good level. For their study, they used a long-term liming rate of 100 kg CaO ha^{-1} yr^{-1}. The average Cd concentration in lime currently available on Swedish markets is circa 0.4 mg Cd (kg CaO)$^{-1}$. This results in annual applications of 0.04 g Cd ha^{-1} yr^{-1}. In France, on total 2.16×10^9 kg of lime was applied to agricultural land (18.4×10^6 ha) in 2007 (Société chimique de France, 2007). This corresponds to an annual application of 120 kg CaO ha^{-1} yr^{-1}. If the Cd concentration is 0.35 (average of Sweden and UK), this is an input of 0.04 g Cd ha^{-1} yr^{-1}. For Germany, about 2×10^6 tonne CaO is spread over a total agricultural area of 17×10^6 ha, which is an application rate of 180 kg CaO ha^{-1} yr^{-1}. Given the large uncertainty on actual application rates, we assumed an average application rate of 250 kg CaO ha^{-1} yr^{-1} and a Cd concentration of 0.35 mg Cd (kg CaO)$^{-1}$ for our calculations. This results in an estimated Cd input of 0.09 g Cd ha^{-1} yr^{-1}. In strong contrast with our results, Nicholson et al. (2003) estimated that Cd inputs are 1.4 g Cd ha^{-1} yr^{-1}, assuming application rates of 4.8 tonnes of CaO ha^{-1} yr^{-1}. It is unlikely that such lime rate reflects the average sustained application rate in EU.

In total we estimate that 0.15 g Cd ha^{-1} yr^{-1} is added to agricultural soils in Europe via manure, sludge and lime applications.

2.5. Output via crop offtake

The Cd removed from soil through the harvested crop, by definition crop offtake, is the product of the yield of the harvested crop and its Cd concentration $[Cd]_{crop}$. The Cd taken up by plants depends on the soil properties and/or plant species. The soil properties typically influencing Cd uptake are the total Cd concentrations, soil pH and the soil organic matter (SOM) content. Increasing the soil Cd concentration increases the crop Cd all other factors being constant; however, the increase is somewhat less than proportional. Overall, regression models can be used to predict the relationship between soil properties and crop Cd concentration (McLaughlin et al., 2011). As shown below, crop offtake

Table 2
Cadmium inputs through sludge application in EU-27 + 1.

Country	Sludge application (kg ha^{-1})	Cd content (mg Cd kg^{-1})	Cd application (g Cd ha^{-1} yr^{-1})
Belgium	22.6	1.0–1.5	0.02–0.03
Bulgaria	3.5	1.6	0.01
Czech Republic	40.9	1.5	0.06
Denmark	17.8	1.0	0.02
Estonia	3.1	2.8	0.01
France	27.8	1.3	0.04
Germany	49.6	1.0	0.05
Lithuania	11.3	1.3	0.01
Spain	82.1	2.1	0.17
Sweden	21.4	0.9	0.02
United Kingdom	203.4	1.3	0.26
Nicholson et al. (2003)	40.0	3.4	0.14
Norway	73.8	0.4	0.03
EU27 + 1 average (without Spain and UK)	26.0	1.8	0.05 (0.03)

Total quantity of sludge spread on agricultural land (EUROSTAT, 2012) was used to calculate the sludge application rate (kg sludge ha^{-1}), assuming sludge is spread over the entire arable land. The Cd concentrations measured in the sludge (EC, 2001) were used to estimate the annual Cd application rates (g Cd ha^{-1} yr^{-1}) on arable land.

is small relative to the other Cd fluxes, hence a high precision in predicting Cd uptake is not required. To simplify the analysis, it is justified to assume that the Cd concentration in the crop changes proportionally with the soil Cd concentration (McLaughlin et al., 2011). This relationship is typically described by a transfer function (TF), i.e. the ratio of the Cd concentration in the crop and the soil Cd concentration, here both expressed a dry weight basis (mg (kg DM or dry soil)$^{-1}$):

$$\mathrm{TF} = \frac{[\mathrm{Cd}]_{\mathrm{crop}}}{[\mathrm{Cd}]_{\mathrm{soil}}}. \tag{2}$$

The Cd concentration in the crops can thus be derived from the soil Cd concentration. Several studies (Eriksson et al., 1996; Mench et al., 1997; Smolders et al., 2007; Wiersma et al., 1986) provide paired soil and crop data which allows the calculation of the TF. According to different studies, the TF for cereal grain ranges between 0.11 and 0.20 and is on average 0.14, whilst for potato an average TF of 0.06 was found (Table 3). The above-mentioned studies allow refining the assessment by including effects on soil properties, e.g. soil pH or total soil Cd, on the TF. As will be shown below, this hardly affects the soil balance. Existing regression models show that the $[\mathrm{Cd}]_{\mathrm{crop}}/[\mathrm{Cd}]_{\mathrm{soil}}$ ratio of winter wheat decreases less than 20% by increasing soil Cd from 0.2 to 0.6 mg Cd kg^{-1} (Eriksson et al., 1996). This justifies the use of the linear TF concept within the relevant Cd concentration range.

The European average yield for cereals is 5.1 tonnes grain per ha and 25.9 tonnes potato tubers per ha (Fertilizers Europe, 2011). At the average soil Cd concentration of 0.28 mg Cd kg^{-1}, this results in a crop offtake of 0.2 g Cd ha^{-1} yr^{-1} for cereals, 0.44 g Cd ha^{-1} yr^{-1} for potatoes and 0.38 g Cd ha^{-1} yr^{-1} for the rotation cereals (2 years) and potatoes (1 year).

2.6. Output via leaching

Leaching (g ha^{-1} yr^{-1}) represents an outflow of Cd from the top soil. There are different models predicting the vertical leaching of Cd, taking into account the retardation, flow rate, vertical dispersion, vertical heterogeneity in Cd binding properties and climatic data (e.g. Streck and Richter, 1997). Such information is not available at a large scale and mass balance approaches typically simplify the calculation by estimating it from the precipitation excess (F; m yr^{-1}) and the dissolved Cd concentration in the soil solution or pore water ($[\mathrm{Cd}]_{\mathrm{solution}}$; mg Cd L^{-1}) (Eq. (3)):

$$\mathrm{Leaching} = 10\ 000\ \ F\ \ [\mathrm{Cd}]_{\mathrm{solution}}. \tag{3}$$

The average precipitation excess in Europe is estimated to be 0.2 m yr^{-1}. For the Mediterranean region this can be reduced to 0.05 m yr^{-1} and for regions with high rainfall a precipitation excess of 0.3 m yr^{-1} was used.

The pore water Cd concentrations change almost proportionally with total soil Cd (keeping all other parameters constant). The K_D value (L kg^{-1}) represents partitioning of Cd between the solid phase $[\mathrm{Cd}]_{\mathrm{soil}}$ and solution phase or pore water (water held in pore space between soil particles), $[\mathrm{Cd}]_{\mathrm{solution}}$:

$$K_D = \frac{[\mathrm{Cd}]_{\mathrm{soil}}}{[\mathrm{Cd}]_{\mathrm{solution}}}. \tag{4}$$

The Cd concentrations in European agricultural soils are typically <1 mg Cd kg^{-1}, concentrations at which sorption is linear (Christensen, 1984).

Different empirical regression models for predicting K_D values in soils from soil properties are in use (Degryse et al., 2009). In these models, log K_D values measured on a set of soils are related to a range of soil properties, for example:

$$\log\ K_D = a + b\ \ \mathrm{pH}_{\mathrm{CaCl2}} + c\ \ \log(\mathrm{OC}) \tag{5}$$

in which OC is the percentage of organic carbon in a soil and $\mathrm{pH}_{\mathrm{CaCl2}}$ is the soil pH measured in 0.01 M $CaCl_2$. Soil pH determines the K_D most sensitively (Degryse et al., 2009).

Paired measurements of Cd in soil solution and Cd in soil were recently collected from previous studies conducted on European soils (Degryse et al., 2009) and these were complemented with some additional studies (Table 4). When $\mathrm{pH}_{\mathrm{H2O}}$ was available a conversion was made to reflect $\mathrm{pH}_{\mathrm{CaCl2}}$. We set selection criteria on these data. First, total soil Cd concentrations were required rather than a fraction of that (e.g. labile soil Cd concentrations) since the soil mass balance described below predicts the changes in total soil Cd only. Second, the determination of the Cd concentration in the solution phase is critical. In situ soil solution or pore water measurements should be used for predicting in situ migration of Cd through soils (Degryse et al., 2009). With in situ measurements the ionic strength and soil pH are not altered and the dissolved organic matter (DOM), known to influence Cd availability, is not diluted. As such, the true in situ Cd concentration can be predicted. The isolation of pore water is usually obtained by centrifugation or by using Rhizon samplers. In total, four studies were found to comply with our criteria, resulting in a total of 151 observations. An overview of K_D models is presented in Table 4.

To select the best K_D model, we have evaluated proposed K_D models against the total data set ($n = 151$). For this, we analysed the logarithmic relationship between the predicted pore water concentrations ($=[\mathrm{Cd}]_{\mathrm{soil}} / K_D$) by each K_D model and the measured pore water concentrations ($[\mathrm{Cd}]_{\mathrm{solution}}$). The strongest relationship was found in model 5 ($R^2 = 0.81$), followed by model 2 ($R^2 = 0.80$) and model 4 ($R^2 = 0.80$). Model 5, a model developed using all available observations, was selected for further calculations. Fig. 2 shows the good fit between measured and predicted soil Cd using model 5 when restricting the analysis to soils with total Cd < 1 mg Cd kg^{-1}, i.e. the soil most representative for agricultural soils. This graph also demonstrates that the used

Table 3
The Cd soil–plant transfer factors (TFs) for cereals (wheat) grown in selected agricultural soils.

Crop	Country	$[\mathrm{Cd}]_{\mathrm{crop}}$ µg Cd (kg fresh weight)$^{-1}$	$[\mathrm{Cd}]_{\mathrm{soil}}$ µg Cd kg^{-1}	TF
Wheat grain	UK	38 (dry weight basis)	700	0.055
	France	58	435	0.11
	The Netherlands	60	400	0.15
	Sweden	40–69	270–420	0.14–0.20
	Germany	56	440	0.13
	Average	57		0.14
Potato	Sweden	10	270	0.04
	The Netherlands	30	400	0.08
	Germany	30	440	0.07
	Average	23		0.06

The TFs are calculated as the ratio of $[\mathrm{Cd}]_{\mathrm{crop}}$ and $[\mathrm{Cd}]_{\mathrm{soil}}$ (Eq. (1)). For more information on original references, we refer to the EU (2007).

Table 4
Selected regression models for K_D derived from pore water-based K_D measurements. The number of observations used to derive the empirical model (n) and the R^2 value for the linear relationship log (K_D measured) and log (K_D predicted by the model).

Model	Log K_D = a + b pH + c log (% OC) a	b	c	n	R^2	Based on data from
1	−1.14	0.56	0.88	56	0.67	Degryse et al. (2003)
2	−0.55	0.43	0.70	47	0.75	de Groot et al. (1998)
3	−2.35	0.78	0.43	31	0.81	McGrath (personal communication)
4	−0.74	0.44	0.90	17	0.79	Nolan et al. (2005)
5	−0.94	0.51	0.79	151	0.71	All data compiled

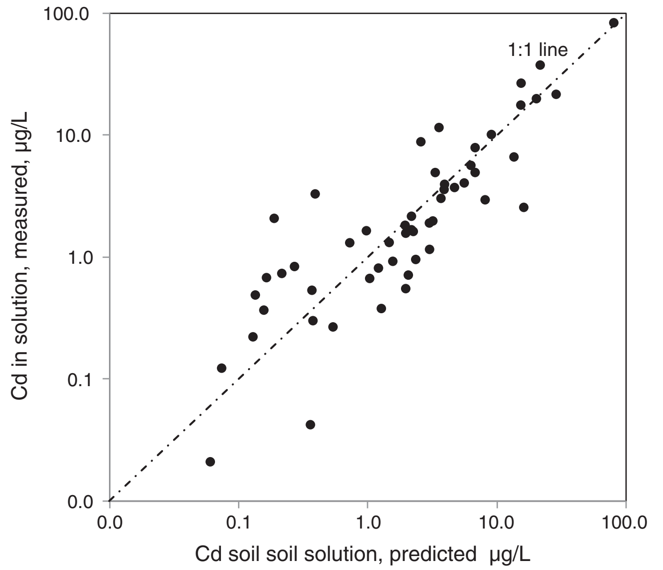


Fig. 2. Predicted (using model 5) and observed soil solution Cd concentration for all soils (pH 3.0–8.6) with total Cd < 1 mg Cd kg^{-1}.
Data from Degryse et al. (2003), de Groot et al. (1998), McGrath (personal communication) and Nolan et al. (2005).

K_D model does not overestimate the dissolved Cd concentration and thus not overestimate leaching.

In 2012, soil pH (0.01 M $CaCl_2$) and organic C content (% OC) were measured over 2000 soil samples from arable land (NGU, 2012). The average soil pH_{CaCl2} of arable soils in Europe is 5.8 (with standard deviation 1.1) and arable soils contain on average 2.5% OC (standard deviation is 1.93% OC). The average leaching is 2.56 g Cd ha^{-1} yr^{-1} when the drainage rate is 0.2 m yr^{-1}. As will be discussed in detail below, this estimate is extremely sensitive to soil pH and to a lesser extent to OC content, which results in a statistical uncertainty of the predicted K_D value. Several studies use a constant leaching flux, e.g. Sternbeck et al. (2011) and Jeng and Singh (1995), fixed at 0.4 g Cd ha^{-1} yr^{-1} for Swedish soils. Moolenaar and Lexmond (1998) derived adsorption models for Cd in the lab, but emphasized that the laboratory situation does not exactly reflect the field situation. They used a leaching loss flux of 1.6 g Cd ha^{-1} yr^{-1}.

3. Model application

The mass balance model (Eq. (1)) was used to predict future Cd concentrations in soils used for arable production (cereals and potatoes). The mass balance used is dynamic, i.e. the output by leaching or crop offtake changes with changing total soil Cd concentrations (de Meeûs et al., 2002). Inputs of Cd are assumed constant over the next 100 years.

The long-term change in soil Cd was calculated from the initial soil Cd concentration ($[Cd]_{soil,\,0}$) and the soil Cd concentration after 100-year application of fertilizers ($[Cd]_{soil,\,100}$) as:

$$\%\text{change} = \frac{[Cd]_{soil,0} - [Cd]_{soil,100}}{[Cd]_{soil,0}} \times 100. \qquad (6)$$

This mass balance is made for the conditions representative for the average in EU27 + 1. Next to the estimation of the EU average, a full factorial analysis was used. The model parameters used to obtain the different scenarios under cereal and potato cropping systems are shown in Table 5. Modelling of the future long-term changes in soil Cd concentrations in agricultural top soils predicts soil Cd concentrations to decrease by 15% over the next 100 years in an average scenario, the P10 and P90 range of scenarios are a 64% decrease and a 12% increase (Fig. 3). The scenario's are highly affected by soil pH and, at the average EU soil pH (in $CaCl_2$), most scenarios (up to P75 of scenarios) are negative.

Table 5
Model parameters used for the full factorial analysis to predict the long-term changes of soil Cd in 540 scenarios.

Model parameters	
Atmospheric deposition	0; 0.35, 0.7 g Cd ha^{-1} yr^{-1}
P application rate, yield and TF	Cereal (monocrop): P-rate = 21 kg P_2O_5 ha^{-1}; Yield = 5.1 tonne ha^{-1}; TF = 0.14
	Cereal – potato rotation: P-rate = 29 kg P_2O_5 ha^{-1}; Yield = 12.1 tonne ha^{-1}; TF = 0.11
	Potato (monocrop): P-rate = 45 kg P_2O_5 ha^{-1}; Yield = 25.9 tonne ha^{-1}; TF = 0.06
% OC	2; 2.5; 3; 4% OC
Soil pH	4.5; 5.5; 5.8; 6.5; 7.5
Cd content of P fertilizer used	36 mg Cd (kg P_2O_5)$^{-1}$
Precipitation excess	0.1; 0.2; 0.3 m yr^{-1}

Next to the European average, the future soil Cd concentration was also predicted for a selection of Member States under cereal cropping systems (Table 6).

In the five regional scenarios, four scenarios have predicted decreases in soil Cd, whereas the scenario for Spain predicts an increase in soil Cd (+15%) (Table 6). This increase is a direct consequence of (i) slow leaching (low precipitation excess), (ii) high soil pH and (iii) relatively high P application rates, when compared to average cereal yields. The 5 regional scenarios reflect regional variability in the Cd mass balance but not parameter uncertainty. Sensitivity analyses are presented to illustrate the most important uncertainties.

3.1. Sensitivity analysis

It is well established that crop offtake strongly depends on the crop type and the soil Cd concentration. Decreasing soil pH enhances crop uptake of Cd. Field data on Cd uptake by numerous plants show that the net effect of increasing soil pH on increasing bioavailability is, on average, only a factor 1.2 per unit pH decrease for maize and potato (McLaughlin et al., 2011; Smolders et al., 2007). This change in TF has only a marginal effect on the Cd balance since crop offtake is small fraction in the Cd mass balance. For example, at the European average, crop offtake is 10-fold smaller than the leaching losses (Table 6).

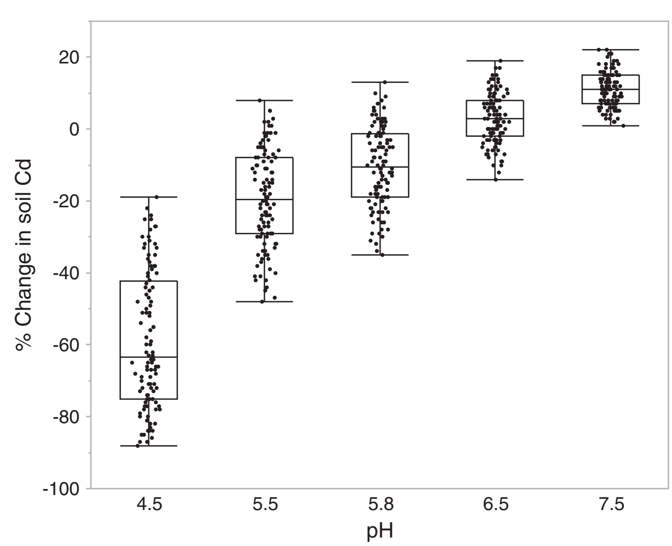


Fig. 3. The predicted % change (min–max and interquartiles; outliers indicated) in soil Cd after 100 years in arable soils for 540 different potential scenarios (Table 5) The median % change is −6%(i.e. decrease), the mean is −15%.

Table 6
Long-term change in soil Cd concentrations after 100-year application of P fertilizers for a set of European countries, with cereals used as reference crop.

Country	Soil properties			Leaching	Atm. Dep.[c]	P fertilizers		Crop yield[f]	Manure[g]	Sludge[h]	Lime[i]	Change in soil Cd	$[Cd]_{soil,\ 100}$
	pH[a]	OC[a]	$[Cd]_{soil,\ 0}$[b]	excess		Application rate[d]	Cd content[e]						
		%	mg Cd kg^{-1}	m yr^{-1}	g Cd ha^{-1}	kg P_2O ha^{-1}	mg Cd $(kg\ P_2O_5)^{-1}$	t ha^{-1}	g Cd ha^{-1}	g Cd ha^{-1}	g Cd ha^{-1}	%	mg Cd kg^{-1}
SE[j]	5.8	4.1	0.25	0.20	0.35	11	4.5	4.7	0.01	0.02	0.04	−15	0.22
DE	6.1	1.7	0.34	0.20	0.25	19	38.9	6.4	0.01	0.05	0.07	−18	0.28
ES	6.4	1.7	0.26	0.05	0.30	28	40.6	3.5	0.01	0.17	0.09	+15	0.30
UK[k]	6.6	2.8	0.30	0.20	0.35	30	22.2	7.0	0.01	0.14	0.14	0	0.30
CZ	5.9	1.9	0.24	0.20	0.40	14	na.	5.6	0.01	0.06	0.09	−12	0.21
EU average	5.8	2.5	0.28	0.20	0.35	21	36.0	5.1	0.01	0.05	0.09	−15	0.24

The parameters used for mass balance calculations for each country are given.
na. Not available.
[a] Soil pH ($CaCl_2$) and OC from agricultural soils were obtained from the GEMAS study (NGU, 2012) unless indicated otherwise.
[b] Initial soil Cd concentration was available from FOREGS and the European risk assessment report (EU, 2007).
[c] Atmospheric deposition (Atm. Dep.) calculated from measurements at EMEP monitoring sites (2012).
[d] P fertilizer application rates for 2010 are available from Fertilizers Europe (2011).
[e] Cd concentration of P fertilizers were obtained from Nziguheba and Smolders (2008), when unavailable the European average as assumed (36 mg Cd $(kg\ P_2O_5)^{-1}$).
[f] Crop offtake was based on cereal production only, a constant TF was assumed at 0.14.
[g] Application rates of manure are assumed constant for all countries (i.e. 0.01 g Cd ha^{-1} yr^{-1}), unless total application rates at country-level are available.
[h] Sludge application rates were calculated as in Table 2.
[i] Unless country averages are available, lime application is estimated to result in 0.09 g Cd ha^{-1} yr^{-1}.
[j] Data on soil properties of agricultural soils in Sweden was obtained from Sternbeck et al. (2011).
[k] Data on soil properties of agricultural soils in UK was obtained from Webb et al. (2001), with conversion of pH (H_2O) to pH ($CaCl_2$).

The predicted leaching highly depends on the reliability of the pore water data. A sensitivity analysis was performed to quantify the effect of the statistical uncertainty of the K_D values on the predicted soil Cd mass balance. From the standard error on the model parameters (fitted by the Equation of model 5 in Table 4), we could estimate the standard deviation on the K_D values from our model for different pH and OC combinations. Fig. 4 shows the variation in percentage change in soil Cd if other parameters are kept constant. Although the error (uncertainty) of K_D is relatively small at low pH compared to high pH, these variations in K_D at low pH will have a much more pronounced effect on the Cd mass balance.

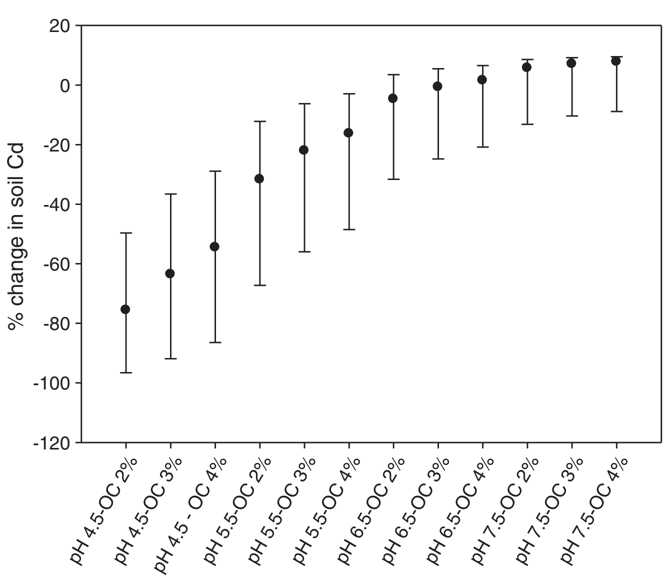


Fig. 4. Uncertainty analysis of the Cd mass balance: effect of uncertainty in K_D values on the % change in soil Cd over 100 years. The error bars represent the 10th and 90th percentile of the predictions based on K_D parameter uncertainty. That uncertainty is based on standard error of parameters of the K_D model (Table 4). Percentage change in soil Cd over 100 years compared to the background Cd concentration (0.3 mg Cd kg^{-1}). For each combination of pH and organic carbon (OC) 1000 simulations were run to cover a full range of K_D values around the mean K_D value. We assumed an atmospheric deposition of 0.35 g Cd ha^{-1} yr^{-1}, a P fertilizer rate of 22 kg P_2O_5 ha^{-1} with 40 mg Cd $(kg\ P_2O_5)^{-1}$, a crop offtake in a cereal monocropping system of 0.21 g Cd ha^{-1} yr^{-1} and a precipitation excess of 0.2 m. The dot represents the predicted flux with mean K_D value.

Leaching is the most important process determining the current mass balance. The predicted annual Cd loss from the plough layer is generally higher than those estimated in most other soil Cd balances (typically < 2 g Cd ha^{-1} yr^{-1}) (Hellstrand and Landner, 1998; Jensen and Bro-Rasmussen, 1992; Moolenaar and Lexmond, 1998; Tjell and Christensen, 1992). In a recent soil Cd mass balance for Australian agricultural soils, predicted leaching of Cd varied from <0.1 g Cd ha^{-1} yr^{-1} in dryland cereal systems to >10 g Cd ha^{-1} yr^{-1} for sugarcane production and annual horticulture, leading to a predicted decline in soil Cd in the future for the latter two scenarios (de Vries and McLaughlin, 2013). That approach used pore water data and excess drainage in the modelled leaching similarly to the approach here. Nicholson et al. (1996) estimated the long-term Cd leaching from the unlimed long-term park grass soils of Rothamsted (UK) using a Cd mass balance. The increase of Cd in the 0–22.5 cm horizon during 1913–1983 was compared with the Cd input by atmospheric deposition (estimated) and by phosphate fertilizers (based on analysis). After accounting for a small (measured) Cd loss by crop offtake, the leaching losses were predicted to range between 0.7 and 3.1 g Cd ha^{-1} yr^{-1} for untreated plots and 2.4 to 4.9 g Cd ha^{-1} yr^{-1} for plots whereto P was applied. The authors estimated a range for the atmospheric Cd input from the average and maximum net annual increase in top soil Cd in 4 different untreated plots of the Rothamsted long-term trials (Jones et al., 1987). Obviously, even the maximum net Cd accumulation in these plots (i.e. 5.4 g Cd ha^{-1} yr^{-1}) is likely lower than the atmospheric Cd input because of Cd losses from these plots. Therefore, the highest estimated Cd leaching from the park grass plots (i.e. 3.1 and 4.9 g Cd ha^{-1} yr^{-1}) may still be conservatively low values. Using our model, we calculated the average annual Cd losses from the P treated plots from the soil properties (soil pH values given in (Nicholson et al., 1994), 0.2 m annual water flux out of the top soil). Our model predicts 4.2 g Cd ha^{-1} yr^{-1} for the P-treated plots. This is within the range of the mass balance estimates of Nicholson et al. (1996).

It is acknowledged that such mass balances do not sensitively prove the Cd leaching. Conceptually, our leaching model assumes that pore water (resident) Cd concentrations denote flux concentrations. Slow desorption of Cd from solid to solution during high flow events may yield lower fluxes of Cd, i.e. flux concentrations may be lower than resident concentrations. However, preferential flow of Cd and colloidal transport may enhance mobility (and result larger losses than predicted) compared to the values predicted from static pore water concentrations. As far as we are aware, only one study has measured

Cd fluxes using wick samplers (flux concentrations) and compared the concentrations with pore water sampled from soil collected near the wick samplers (Degryse and Smolders, 2006). There were three soil profiles at which that was compared and the ratios of Cd concentrations in pore water over those in corresponding leachates (18 months) were 1.4, 0.9 and 1.7, i.e. close to 1.0 corroborating our assumption within that uncertainty. The control site with the lowest soil Cd yielded the largest ratio (1.7). This suggests that our prediction of Cd leaching based on pore water data at low soil Cd may indeed somewhat overestimate Cd leaching.

In another Cd leaching study using 6 different undisturbed pasture soils from New Zealand, it was concluded that the prediction of Cd leaching from pore water composition and rainfall data overestimated Cd leaching by a factor 5, 4 and 2 depending on the soil depth at which the pore water was sampled (Gray et al., 2003). The most relevant depth is the deepest one, corresponding to a factor 2, since the leachate was collected at the bottom of the columns. If correct, the factor 2 has important effects on the estimated EU Cd mass balance. However, the conclusion of that study might be questioned: the soils were undisturbed (unmixed) soil columns, 25 cm high, and Cd concentrations decreased with depth. The pore waters were not collected at the interface where leachates were collected and for which the pore water had to be measured to test the hypothesis whether pore waters denote flux concentrations. In addition, there was no unsaturated water flow since the leachates were collected by gravity, inducing water saturated conditions at the lower interface in which anaerobic conditions develop leading to lower Cd mobility. The higher pH of the leachates than those of the soil is indicative for anaerobic conditions and can reduce local mobility. This suggests that the measured leachate Cd concentrations in that study are lower than values in the field where soils are mainly unsaturated. We have seen such trends before in column studies and concluded that monitoring Cd leaching requires suction to be applied at the bottom of the boundary layer where leachates are collected (Degryse et al., 2007).

A Monte Carlo sensitivity analysis of the projected change in soil Cd was made to identify the variability in Cd trends based on variability of the parameters. This was performed using Risk Solver program for Excel by combining the variability of the atmospheric deposition, P application rate, Cd concentration of P fertilizer, soil pH, OC content and initial soil Cd concentration in Europe and assuming appropriate distributions of the parameters. This analysis entailed 10,000 simulations and again confirmed that soil pH is the most important parameter in predicting long-term change in soil Cd, followed by the initial soil Cd concentration and the OC content of a soil. The Cd concentration of the P fertilizer itself comes only on the fourth position (details of that analysis can be obtained from senior author).

3.2. Comparison with other mass balances

In contrast with other mass balance studies performed in Europe, a net decrease in soil Cd is expected for Europe at the average scenario for cereals (Table 7). In the European Union Cd risk assessment report (EU, 2007), it was calculated that for the European average soil Cd would increase from 0.30 to 0.32 mg Cd (kg soil)$^{-1}$ over 60 years. This difference in result can mainly be attributed to (i) the higher level of P application rate assumed, and (ii) the difference in K_D model used for estimations. In the CSTEE report (2002) soil Cd was estimated to change in 100 years by between −4% and 50% for P fertilizers containing 40 mg Cd (kg P_2O_5)$^{-1}$, which is close to the current European average. Again, different input and output parameters (i.e. atmospheric deposition, leaching, P fertilizer consumption) were assumed (as discussed in detail before). A short overview of similar input and output balances is given in Table 7.

Earlier studies performed by Hutton and Symon (1986) and Nicholson et al. (2003) focussed on making an inventory of Cd inputs to agricultural soils of United Kingdom, whilst in the others output of Cd is also considered. Large differences can be found between previous inventories and more recent estimates (from 2010) for atmospheric deposition, Cd additions by P fertilizers and other diffuse inputs such as manure, lime and sludge. Especially for atmospheric deposition (EMEP/CEIP, 2012a) and P fertilizer use (IFA, 2012), large changes in time have been documented and explain the discrepancy.

There are some data available on recent time trends in Cd concentrations in crops and food. Cadmium concentrations in stored grain samples from a long-term trial in Sweden (60 years: 1918–1980) were measured (Andersson and Bingefors, 1985). An increase was observed up to 1980. Other data from 10 long-term fertilizer trials in Sweden indicate a decreasing trend (about factor 2) in wheat grain between 1980 and 2003 (Kirchmann et al., 2009). The food monitoring programme in Germany noted that wheat grain Cd concentrations decreased from about 0.05 to 0.04 mg Cd kg^{-1} between 1995 and 2005. Such parallel trends in atmospheric deposition (Kirchmann

Table 7
An overview of inputs and outputs (g Cd ha^{-1} yr^{-1}) considered in different European Cd mass balance studies or input inventories.

Reference	Hutton and Symon (1986)	Alloway and Steinnes (1999)	Moolenaar and Lexmond (1998)	Nicholson et al. (2003)	CSTEE (2002)	Sternbeck et al. (2011)	Belon et al. (2012)	Update (2010 as reference)
Country of relevance	UK	Europe	The Netherlands	UK	EU15	Sweden	France	EU27 + 1
Inputs								
Atm. Dep.	3.00	3.00	1.30	1.90	3.00	0.31–0.39	0.25	0.35
P fertilizers	4.40	2.50	1.50–2.50	1.60	0.46–4.14[a]	0.10–0.60[a]	0.98	0.79
Manure and compost	nd.	nd.	0.05	1.4 to 6[b]	nd.	nd.	0.44	0.01
Sewage sludge	0.9	nd.	nd.	0.14	nd.	0.06–0.55[c]	0.08	0.05
Lime	nd.	nd.	nd.	0.14	nd.	0.04	0.04	0.09
Total input	>8.3	>5.5	>2.85–3.85	5.18–9.78	>3.46–7.14	>0.51–1.58	1.79	1.29
Outputs								
Crop offtake	nd.	nd.	0.65[d]	nd.	0.3[e]	0.25–0.84[e]	nd.	0.20[e]
Leaching	nd.	nd.	1.60	nd.	0.31–9.8[f]	0.4[g]	nd.	2.56
Total output	nd.	nd.	2.25	nd.	0.6–10.1	0.65–1.24	nd.	2.76

For this study only the European average was considered.
nd. Not determined or not considered in the study.
[a] Depending on the Cd concentration of the P fertilizer (20, 40 or 60 mg Cd (kg P_2O_5)$^{-1}$) and P fertilizer rate (23 or 69 kg P_2O_5 ha^{-1}) used in calculations.
[b] Depending on the type of manure considered in calculations.
[c] P loads similar to P loads given as mineral fertilizer.
[d] Crop offtake by arable crops only, constant annual crop offtake.
[e] Crop offtake at t = 0 (initial soil Cd concentration is 0.28 mg Cd kg^{-1}), but changes with soil Cd concentration via a transfer function.
[f] Depending on the K_D model (Römkens and Salomons, 1998; McBride et al., 1997) and precipitation excess (0.1 or 0.4 m yr^{-1}) used in calculations.
[g] Leaching is assumed independent of changes in soil Cd concentration, pH and OC.

et al., 2009) may also be affected by recovery from acid rain or declining soil Cd.

3.3. Uncertainties in long-term Cd predictions

The predictions of long-term changes in soil Cd concentrations have relied on the business as usual assumption. This results in an oversimplification of reality as changes can be expected in terms of P fertilizer use, agricultural practices including soil pH control and climate. However, given that no reliable future scenarios can be developed for the all factors; we refrained from making simulations. From the above it is clear than changes in soil pH are likely to have most significant impacts on the balance at current low level input scenarios.

4. Conclusions

The current EU Cd mass balance in a scenario with EU average input/output is negative compared to positive balances for the similar cases that were estimated 10 or more years ago. Soil Cd in cereal and potato cropping systems is predicted to decrease by, on average, 15% over the next 100 years whilst the P10 and P90 range of scenarios are a 64% decrease to a 12% increase. This negative input–output balance was obtained due to the strong reduction of atmospheric Cd deposition data and reduced P fertilizer consumption rates. The predicted regional trends in EU range between 15% increase (e.g. Spain) and 21% decrease (e.g. United Kingdom) and mainly relate to differences in soil pH, precipitation or drainage excess, and fertilizer application rates.

Acknowledgements

We acknowledge Fertilizers Europe for financing this study.

References

Alloway BJ, Steinnes E. Anthropogenic additions of cadmium to soil. In: McLaughlin MJ, Singh BR, editors. Cadmium in soils and plants. Dordrecht, the Netherlands: Kluwer Academic Publishers; 1999. p. 97–123.

Andersson A, Bingefors S. Trends and annual variations in Cd concentrations in grain of winter wheat. Acta Agric Scand 1985;35:339–44.

Belon E, Boisson M, Deportes IZ, Eglin TK, Feix I, Bispo AO, Galsomies L, Leblond S, Guellier CR. An inventory of trace elements inputs to French agricultural soils. The Science of the Total Environment 2012;439:87–95.

Christensen TH. Cadmium soil sorption at low concentrations. I. Effect of time, cadmium load, pH, and calcium. Water Air Soil Pollut 1984;21:105–14.

CSTEEIn: Protection ECD-ghac, editor. Member state assessments of the risk to health and environment from cadmium in fertilizers; 2002. [Brussels].

de Groot AC, Peijnenburg WJGM, van den Hoop MAGT, Ritsema R, van Veen RPM. Zware metalen in Nederlandse veldbodems: een experimentele en theoretische studie over evenwichtspartitie. Rijksinstituut voor Volksgezondheid en Milieu RIVM; 1998.

de Meeûs C, Eduljee GH, Hutton M. Assessment and management of risks arising from exposure to cadmium in fertilisers. I. Sci Total Environ 2002;291:167–87.

de Vries W, McLaughlin MJ. Modeling the cadmium balance in Australian agricultural systems in view of potential impacts on food and water quality. Sci Total Environ 2013; 461:240–57.

Degryse F, Smolders E. Mobility of Cd and Zn in polluted and unpolluted Spodosols. Eur J Soil Sci 2006;57:122–33.

Degryse F, Broos K, Smolders E, Merckx R. Soil solution concentration of Cd and Zn can be predicted with a $CaCl_2$ soil extract. Eur J Soil Sci 2003;54:149–58.

Degryse F, Vlassak V, Smolders E, Merckx R. Mobilization of Cd upon acidification of agricultural soils: column study and field modelling. Eur J Soil Sci 2007;58:152–65.

Degryse F, Smolders E, Parker DR. Partitioning of metals (Cd, Co, Cu, Ni, Pb, Zn) in soils: concepts, methodologies, prediction and applications — a review. Eur J Soil Sci 2009;60:590–612.

DG Enterprise. Draft proposal relating to cadmium in fertilizers; 2003.

ECIn: Environment D, editor. Survey of wastes spread on land — final report; 2001. [Brussels].

EMEP. Heavy metals and POP measurements, 2010; 2012.

EMEP/CEIP. EMEP/CEIP public database WebDab; 2012a.

EMEP/CEIP. Long-term changes of heavy metal transboundary pollution of the environment (1990–2012); 2012b.

Eriksson J, Öborn I, Jansson G, Andersson A. Factors influencing Cd-content in crops. Results from Swedish field investigations. Swed J Agric Res 1996;26:125–33.

EU. European Union risk assessment report. Cadmium metal. Part I environment, 72. Luxembourg: Office for Official Publications of the European Communities; 2007.

EUROSTAT. Statistics by the European Commission; 2012.

Fertilizers Europe. Forecast of food, farming and fertilizer use 2012–2022; 2011 [Brussels].

FOREGS. Geochemical atlas of Europe, part 2 — interpretation of geochemical maps, additional tables, figures, maps and related publications. Geological Survey of Finland; 2006. [Espoo].

Gray CW, McLaren RG, Roberts AHC. Cadmium leaching from some New Zealand pasture soils. Eur J Soil Sci 2003;54:159–66.

Groenenberg JE, Romkens PFAM, Comans RNJ, Luster J, Pampura T, Shotbolt L, et al. Transfer functions for solid-solution partitioning of cadmium, copper, nickel, lead and zinc in soils: derivation of relationships for free metal ion activities and validation with independent data. Eur J Soil Sci 2010;61:58–73.

Harmens H, Ilyin I, Mills G, Aboal JR, Alber R, Blum O, et al. Country-specific correlations across Europe between modelled atmospheric cadmium and lead deposition and concentrations in mosses. Environ Pollut 2012;166:1–9.

Hellstrand S, Landner L. Cadmium in fertilizers, soil, crops and foods — the Swedish situation. Cadmium exposure in the Swedish environment. KEMI report; 1998.

Hutton M. A prospective atmospheric emission inventory for cadmium — the European Community as a study area. Sci Total Environ 1983;29:29–47.

Hutton M, Symon C. The quantities of cadmium, lead, mercury and arsenic entering the U.K. environment from human activities. Sci Total Environ 1986;57:129–50.

Ifa D. International fertilizer industry association — statistics; 2012.

IPCS. Cadmium. Environmental health criteria, 134. Geneva: World Health Organisation; 1992.

Järup L, Berglund M, Elinder CG, Nordberg G, Vahter M. Health effects of cadmium exposure—a review of the literature and a risk estimate. Scand J Work Environ Health 1998;24:1–52.

Jeng AS, Singh BR. Cadmium status of soils and plants from a long-term fertility experiment in southeast Norway. Plant and Soil 1995;175:67–74.

Jensen H, Bro-Rasmussen F. Environmental cadmium in Europe. Rev Environ Contam Toxicol 1992;125:101–81.

Jones KC, Johnston AE. Cadmium in cereal grain and herbage from long-term experimental plots at Rothamsted, UK. Environ Pollut 1989;57:199–216.

Jones KC, Symon CJ, Johnston AE. Retrospective analysis of an archived soil collection: II cadmium. Sci Total Environ 1987;67:75–89.

Juste C, Tauzin J. Evolution du contenu en métaux lourds d'un sol de limon maintenu en jachère nue après 56 années d'application continu de divers d'engrais et amendements. C R Acad Agric Fr 1986;72:739–46.

Kiene A. Calculating input and output of heavy metals in soil. The case of cadmium. Plant impact at contaminated sites. International workshop., Schmallenberg, Germany; 1999. p. 43–56.

Kirchmann H, Mattsson L, Eriksson J. Trace element concentration in wheat grain: results from the Swedish long-term soil fertility experiments and national monitoring program. Environ Geochem Health 2009;31:561–71.

McBride M, Sauve S, Hendershot W. Solubility control of Cu, Zn, Cd and Pb in contaminated soils. Eur J Soil Sci 1997;48:337–46.

McLaughlin MJ, Smolders E, Degryse F, Rietra R. Uptake of metals into vegetables. In: Swartjes F, editor. Dealing with contaminated sites. From theory towards practical application. Dordrecht: Springer; 2011.

Mench M, Baize D, Mocquot B. Cadmium availability to wheat in five soil series from the Yonne district, Burgundy, France. Environ Pollut 1997;95:93–103.

Milieu, WRc, RPA. Environmental, economic and social impacts of the use of sewage sludge on land — final report; 2008.

Moolenaar SW, Lexmond TM. Heavy-metal balances of agro-ecosystems in the Netherlands. Neth J Agric Sci 1998;46:171–92.

NGU. The EuroGeoSurveys geochemical mapping of agricultural and grazing land soils project (GEMAS). Evaluation of quality control results of total C and S, total organic carbon (TOC), cation exchange capacity (CEC), XRF, pH, and particle size distribution (PSD) analysis; 2012. p. 90.

Nicholson FA, Jones KC, Johnston AE. Effect of phosphate fertilizers and atmospheric deposition on long-term changes in the cadmium content of soils and crops. Environ Sci Technol 1994;28:2170–5.

Nicholson FA, Jones KC, Johnston AE. Evidence for the leaching of surface deposited cadmium in agricultural soils. In: Development of ECa, editor. Fertilizers as a source of cadmium Paris; 1996. p. 218–31.

Nicholson FA, Smith SR, Alloway BJ, Carlton-Smith C, Chambers BJ. An inventory of heavy metals inputs to agricultural soils in England and Wales. Sci Total Environ 2003;311: 205–19.

Nolan AL, Zhang H, McLaughlin MJ. Prediction of zinc, cadmium, lead, and copper availability to wheat in contaminated soils using chemical speciation, diffusive gradients in thin films, extraction, and isotopic dilution techniques. J Environ Qual 2005;34: 496–507.

Nziguheba G, Smolders E. Inputs of trace elements in agricultural soils via phosphate fertilizers in European countries. Sci Total Environ 2008;390:53–7.

Pacyna EG, Pacyna JM, Fudala J, Strzelecka-Jastrzab E, Hlawiczka S, Panasiuk D, et al. Current and future emissions of selected heavy metals to the atmosphere from anthropogenic sources in Europe. Atmos Environ 2007;41:8557–66.

Pacyna JM, Pacyna EG, Aas W. Changes of emissions and atmospheric deposition of mercury, lead, and cadmium. Atmos Environ 2009;43:117–27.

Römkens PFAM, Salomons W. Cd, Cu and Zn solubility in arable and forest soils: consequences of land use changes for metal mobility and risk assessment. Soil Sci 1998; 163:859–71.

Rothbaum HP, Goguel RL, Johnston AE, Mattingly GEG. Cadmium accumulation in soils from long-continues applications of superphosphate. J Soil Sci 1986;37:99–107.

Smolders E, Mertens J. Cadmium. In: Alloway BJ, editor. Heavy metals in soils, 22. Netherlands: Springer; 2013. p. 283–311.

Smolders E, Jansson G, Van Laer L, Ruttens A, Vangronsveld J, Römkens P, et al. Teeltadvies voor de landbouw in kader van het Interreg project BeNeKempen; 2007.

Société chimique de France. Carbonate de calcium; 2007.

Sternbeck J, Eriksson J, Österas AHIn: Commission E, editor. The role of mineral fertilisers for cadmium in Swedish agricultural soil and crops; 2011.

Streck T, Richter J. Heavy metal displacement in a sandy soil at the field scale. 2. Modeling. J Environ Qual 1997;26:56–62.

Tjell JC, Christensen TH. Evidence of increasing cadmium contents of agricultural soils. Heavy metals in the environment, 2. Athens: Lekkas, T.D.L.; 1985.

Tjell JC, Christensen TH. Sustainable management of cadmium in Danish agriculture. Impact Heavy Met Environ 1992;2:273–86.

Webb J, Loveland PJ, Chambers BJ, Mitchell R, Garwood T. The impact of modern farming practices on soil fertility and quality in England and Wales. J Agric Sci 2001;137:127–38.

Wiersma D, Vangoor BJ, Vanderveen NG. Cadmium, lead, mercury, and arsenic concentrations in crops and corresponding soils in the Netherlands. J Agric Food Chem 1986;34:1067–74.

Exhibit 2
Heat Island Executive Summary

S·POWER
An AES and AIMCo Company

Heat Island Effect Literature Review
Executive Summary

The heat island effect is a term that refers to increased ambient temperatures in both natural and urban environments due to land use changes. This effect is most prevalent in urban environments as a result of increased development such as converting vacant land into a shopping center. Limited empirical data exists regarding the heat island effect resulting from the installation of solar energy facilities. Most studies rely on models that produce varying results, with some even suggesting that solar energy facilities result in a cooling effect on local environments.[1]

One of the few studies that collected empirical data regarding the heat island effect from solar energy facilities focused on a desert ecosystem in Arizona. The study monitored ambient temperatures for over one year using aspirated temperature probes (2.5 meters above the soil surface) at three nearby sites (within 1 km^2) that included a solar energy facility, an urban parking lot, and a natural semiarid desert ecosystem. The study concluded that the average annual temperature within the solar arrays at the solar energy facility was 22.7°C + 0.5°C, while the nearby desert ecosystem was 20.3°C + 0.5°C, thus indicated a slight heat island effect.[2]

However, it should be noted that the study was limited in its scope in that it only measured ambient temperatures at the three locations, and not the transfer or attenuation of heat from one location to another. The study also indicates results would be different if conducted in an ecosystem comparable to the Project Site that is surrounded by dense vegetation, forested areas, varying topography, higher annual precipitation, and perennial wetlands, rather than a desert ecosystem. While the Project may induce a minimal heat island or slight cooling effect within the PV solar arrays, it is expected that this increase in ambient temperature would rapidly attenuate with distance from the PV solar arrays due to the surrounding environment (e.g., vegetation, topography, weather, wetlands).

Another model-based study found that slightly elevated temperatures within the solar field quickly dissipated and returned to ambient temperatures both above and at the perimeter of the solar array. It also found that on most days the solar array cooled completely at night, making a heat island effect even less likely.[3]

As stated above, the Project is currently being designed to allow for maximum setbacks (beyond 50 feet) from adjacent property owners, with the intent of achieving a minimum 250-foot setback from all Fawn Lake property lines. sPower is maintaining and/or installing vegetative buffers and berms that would further reduce heat emanating from the PV solar arrays through absorption; thereby preventing a heat island effect on neighboring properties. And lastly, sPower's operations and maintenance staff regularly work within operating solar arrays on existing solar energy facilities in desert regions and are never exposed to unsafe temperature levels.

---

[1] Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X. & Lemonsu, A. Solar panels reduce both global warming and Urban Heat Island. *Frontiers in Environmental Science* 2, 14, doi: 10.3389/fenvs.2014.00014. (2014).
[2] Barron-Gafford, Greg, R., Minor, N., Allen, A., Cronin, A., Brooks. & M., Pavao-Zuckerman. The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Scientific Reports*, doi: 10.1038/srep35070. (2016).
[3] Fthenakis, Vasilis & Yu, Yuanhao. (2013). Analysis of the potential for a heat island effect in large solar farms. Conference Record of the IEEE Photovoltaic Specialists Conference. 3362-3366. 10.1109/PVSC.2013.6745171.

Appendix:
References Cited

frontiers in
ENVIRONMENTAL SCIENCE

ORIGINAL RESEARCH ARTICLE
published: 04 June 2014
doi: 10.3389/fenvs.2014.00014

Solar panels reduce both global warming and urban heat island

Valéry Masson[1]*, Marion Bonhomme[2], Jean-Luc Salagnac[3], Xavier Briottet[4] and Aude Lemonsu[1]

[1] Météo-France/CNRS, Centre National de Recherches Météorologiques/Groupe d'étude de l'atmosphère Météorologique, Toulouse, France
[2] Laboratoire de Recherche en Architecture, Toulouse, France
[3] Centre Scientifique et Technique du Bâtiment, Marne-La-Vallée, France
[4] French Center for Aerospatial Research, Toulouse, France

Edited by:
Rémy Roca, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, France

Reviewed by:
Bijoy Vengasseril Thampi, Science Systems and Applications, Inc., USA
David J. Sailor, Portland State University, USA

****Correspondence:***
Valéry Masson, Météo-France/CNRS, Centre National de Recherches Météorologiques/Groupe d'étude de l'atmosphère Météorologique, 42 av Coriolis, 31057 Toulouse, France
e-mail: valery.masson@meteo.fr

The production of solar energy in cities is clearly a way to diminish our dependency to fossil fuels, and is a good way to mitigate global warming by lowering the emission of greenhouse gases. However, what are the impacts of solar panels locally? To evaluate their influence on urban weather, it is necessary to parameterize their effects within the surface schemes that are coupled to atmospheric models. The present paper presents a way to implement solar panels in the Town Energy Balance scheme, taking account of the energy production (for thermal and photovoltaic panels), the impact on the building below and feedback toward the urban micro-climate through radiative and convective fluxes. A scenario of large but realistic deployment of solar panels on the Paris metropolitan area is then simulated. It is shown that solar panels, by shading the roofs, slightly increases the need for domestic heating (3%). In summer, however, the solar panels reduce the energy needed for air-conditioning (by 12%) and also the Urban Heat Island (UHI): 0.2 K by day and up to 0.3 K at night. These impacts are larger than those found in previous works, because of the use of thermal panels (that are more efficient than photovoltaic panels) and the geographical position of Paris, which is relatively far from the sea. This means that it is not influenced by sea breezes, and hence that its UHI is stronger than for a coastal city of the same size. But this also means that local adaptation strategies aiming to decrease the UHI will have more potent effects. In summary, the deployment of solar panels is good both globally, to produce renewable energy (and hence to limit the warming of the climate) and locally, to decrease the UHI, especially in summer, when it can constitute a health threat.

Keywords: urban heat island, solar energy, solar panels, cities, adaptation to climate change

1. INTRODUCTION

Renewable energy is seen as a necessary step toward sustainable energy development, diminution of the use of fossil fuels and mitigation of climate change, as stated for example by Elliott (2000): "With concerns about Climate Change growing, the rapid development of renewable energy technologies looks increasingly important." However, the recent analysis of Nugent and Sovacool (2014) showed that, when their complete life-cycle is considered, renewable energies are not CO_2 sinks yet. Nevertheless their greenhouses gas emission rate per unit of energy produced is much less than for energy sources based on fossil fuels and slightly less than for nuclear power. They also "uncover best practices in wind and solar design and deployment that can better inform climate change mitigation efforts in the electricity sector." Elliott (2000) underlines that renewable energy deployment requires a new paradigm, of decentralized energy production and small production systems. The implementation of renewable energy will need social and institutional changes, even if technology for these systems already exists (Gross et al., 2003, while still needing improvements and further research Jader-Waldau, 2007). Funding, incentive policies and statutory obligations on electricity suppliers may be needed to develop renewable energy faster. Lund (2007) demonstrates that, in Denmark, a transition toward 100% of renewable energy production is possible. Sovacool and Ratan (2012) conclude that nine factors linked to policy, social and market aspects favor or limit the development of wind turbines and solar energy, and explain why renewable energy is growing fast in Denmark and Germany compared to India and the USA.

Sims et al. (2003) show that most renewable energies can, in certain circumstances, reduce cost as well as CO_2 emissions, except for solar power, which remains expensive. However, Hernandez et al. (2014) review the environmental impacts of utility-scale solar energy installations (solar farms), which are typically implemented in rural areas, and show that they have low environmental impacts relative to other energy systems, including other renewables. Furthermore, solar power is also one of the few renewable energy sources that can be implemented on a large scale within cities themselves. Arnette (2013) shows that, compared to solar farms, individual rooftop solar panels are a very cost-effective means of increasing renewable energy generation and decreasing greenhouse gas emissions. So they conclude that solar panel implementation on roofs should be part of a balanced approach to energy production. Here, we aim to evaluate the environmental impacts on the local climate, of implementing such a strategy at city scale.

The main impact of cities on the local weather is the Urban Heat Island (UHI). Cities are warmer than the surrounding countryside, and this can lead to a health crisis during heat waves, as was the case in Paris in 2003 with 15,000 premature deaths (Fouillet et al., 2006) or in Moscow with 11,000 premature deaths in 2010 (Porfiriev, 2014). It also has to be considered that, due to climate warming, the UHI impacts will become even larger than they are now (Lemonsu et al., 2013). Therefore, several strategies are being studied to reduce the UHI in summer. Gago et al. (2013) have reviewed several research works analyzing strategies to mitigate the UHI, including changes in green spaces, trees, albedo, pavement surfaces, vegetation, and building types and materials. Santamouris et al. (2011) have reviewed of several advanced cool materials systems usable to reduce the UHI. Such materials could be implemented on roofs in order to reflect more energy to the sky (high albedo, high emissivity) or to delay the heat transfer toward the inside the building (phase change materials). Masson et al. (2013) showed that changes in agricultural practices in the vicinity of Paris and the use of cool materials for roofs and pavement would decrease the UHI by 2 K and 1 K, respectively. However, the question of the ability of solar panels to contribute to the same goal is not addressed in these papers, and extremely few studies focus on, or even take into account, the effect of solar panels on the UHI.

It is thus necessary to analyze whether the two objectives of mitigating the global climate warming by increasing renewable energy production in cities, especially through solar panels, and of attenuating the UHI are compatible. Solar panels modify the nature of the rooftop and may thus influence the energy transfers to the atmosphere and the resulting UHI. The aim of this paper is then to evaluate the impact of solar panels, known to be good for global warming mitigation, on the local climate, especially the UHI.

2. SOLAR PANELS INTO THE URBAN CANOPY MODEL TEB

The objective of this section is to present how solar panels can be included in the Town Energy Balance (TEB, Masson, 2000) scheme, in terms of both energy production and interactions with the roofs below (shading, modification of the roof energy balance, etc.). The solar panels themselves can be either photovoltaic panels or thermal panels that heat water.

2.1. MODELING STRATEGY

The solar panel exchanges energy with the other components of the system. Very few parameterizations taking these exchanges into account exist in the literature. The level of detail depends strongly on the objectives of the authors. On the one hand, when looking at the building scale, it is possible to consider some implementation characteristics of the panels, as in Scherba et al. (2011), who modified the Energy+ software (software dedicated to building energetics) to improve its previous solar panel model (which only computed the energy production). Their solar panel model considers the tilting of the panels and associated sky-view factors. They then perform an analysis of the impact of several types of roofs on sensible heat fluxes toward the atmosphere, but are unable to link these fluxes to the UHI, which needs to take all the buildings of the entire city into account. On the other hand, Taha (2013) studies the impact of solar panels on the whole urban area of Los Angeles. To do this, he uses the very simplified approach of effective albedo, which accounts for both the albedo and the solar conversion efficiency (linked to the energy produced). This approach estimates the impact on the UHI, but does not take account of the interactions with the urban canopy below (solar panel shadowing may lead to less cooling energy being used in buildings for example, leading to less waste heat outside).

In order to study the impact of solar panels implementations on the urban atmosphere and on the population and buildings, we need an approach that looks at both spatial scales: buildings and city. The TEB scheme is able to simulate the energy, water and momentum exchanges between cities and the atmosphere at a resolution as high as the urban block (say down to 100 m by 100 m). The energetics of buildings have also been included in TEB by Bueno et al. (2012) and Pigeon et al. (2014), to simulate the energy behavior of a typical building representative of the block. The focus is to keep the maximum of key processes, while making some approximations in the geometry that are pertinent at block scale (building shapes are averaged into road canyons, only one thermal zone is kept in the buildings, individual windows are averaged into a glazing fraction, etc.). Gardens and greenroofs modules have also been implemented (Lemonsu et al., 2012; DeMunck et al., 2013a). The modeling strategy chosen here for the implementation of solar panels is similar: key processes are kept while some geometrical assumptions are made to avoid unnecessary details of individual buildings.

In TEB, it is necessary to take account not only of the production of energy by the panels but also the influence of the panels on the underlying roofs. We must therefore calculate the complete energy balance of the panel to determine what is exchanged with the roof or the atmosphere. The TEB model will then be able to estimate the impact of solar panel implementation on the UHI at city scale, as well as the production of energy.

2.2. ENERGY BALANCE OF THE SOLAR PANEL

Geometrically, the solar panels are assumed to be horizontal when calculating the radiative heat exchange with the other elements: exchanges between the roof, the solar panels and the sky above are considered to be purely vertical (**Figure 1**). Note that we take the inclination of the panel into account to calculate the irradiance for power production.

The energy balance equation of the solar panel is written:

$$SW^{\downarrow}_{sky} + LW^{\downarrow}_{sky} + LW^{\uparrow}_{roof} = SW^{\uparrow}_{panel} + LW^{\uparrow}_{panel} + LW^{\downarrow}_{panel} + H + E_{prod} \quad (1)$$

The terms on the left hand side are incoming energy to the solar panel:

- $SW^{\downarrow}_{sky}$ is the incoming Short-Wave radiation from the sun. It can be diffuse or direct, and is considered as forcing data for TEB.
- $LW^{\downarrow}_{sky}$ is the incoming Long-Wave radiation from the atmosphere. It is diffuse and is also used as forcing data for TEB.

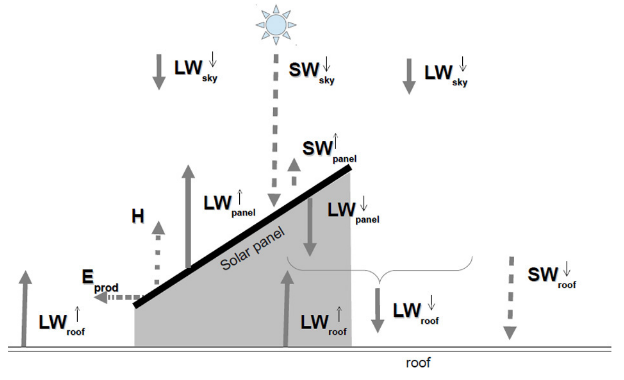


FIGURE 1 | Schematic diagram of the energy balance of the solar panel and its impact on radiation received by the roof (dashed arrows: solar fluxes; plain arrows: long-waves fluxes; dotted arrow: sensible heat flux; dotted-dashed arrow: energy produced).

$LW^{\uparrow}_{roof}$ is the Long-Wave radiation coming up from the roof and being intercepted by the solar panel. It is computed by TEB from the roof emissivity and surface temperature and the long-wave radiation received by the roof:

$$LW^{\uparrow}_{roof} = \epsilon_{roof}\sigma T^4_{roof} + (1 - \epsilon_{roof})LW^{\downarrow}_{roof} \quad (2)$$

The terms on the right hand side of Equation (1) are outgoing energy from the panel:

$SW^{\uparrow}_{panel}$ is the solar radiation reflected by the solar panel. It is classically parameterized using the albedo of the solar panel (α_{panel}): $SW^{\uparrow}_{panel} = \alpha_{panel}SW^{\downarrow}_{panel}$. It is also assumed to go back to the sky (we neglect the effect of the inclination of the solar panel on the direction of the reflected light). According to Taha (2013), the value of the albedo of the solar panel ranges from 0.06 to 0.1. We performed measurements of the albedo for a sample of solar panel (under several inclinations) by integrating the hemispheric directional reflectance measured with a goniometer (see section 2.4 for details). From our measurements, the value of 0.11 is used for α_{panel} in the present paper.

$LW^{\uparrow}_{panel}$ is the long-wave radiation emitted (and reflected) by the solar panel to the sky. It depends on the surface temperature of the solar panel, which is estimated following the ISPRA center method:

$$T_{panel} = T_{air} + k_T Irr \quad (3)$$

where T_{air} is the air temperature, Irr is the irradiance received by the solar panel (cf section 2.5) and k_T is a constant coefficient equal to 0.05 K/(Wm^{-2}). In this formulation, the nocturnal dependency of the panel surface temperature on the sky temperature proposed by Scherba et al. (2011) is not used. It would be an improvement to be considered in the future. Also using the emissivity of the solar panel ϵ_{panel}, equal to 0.93 in our measurements (cf section 2.4), the upward long-wave radiation from the solar panel can be written:

$$LW^{\uparrow}_{panel} = \epsilon_{panel}\sigma T^4_{panel} + (1 - \epsilon_{panel})LW^{\downarrow}_{sky} \quad (4)$$

$LW^{\downarrow}_{panel}$ is the long-wave radiation emitted by the solar panel to the roof (downwards). It is computed under the hypothesis that the temperature of the downward face of the solar panel is always approximately equal to the air temperature. This is probably a limitation of our model during daytime. However, even if the temperature of the downwards face of the solar panel is underestimated (due to the warming of the solar panel and the heat diffusion inside it), this temperature will still be higher than the sky temperature. So, from the point of view of the roof below the solar panel, the incoming radiation will be higher. This captures at least the first order of an effect of the solar panel on the roof. Given the uncertainties, we also neglect the dependency in emissivity for this face of the panel. This gives:

$$LW^{\downarrow}_{panel} = \sigma T^4_{air} \quad (5)$$

E_{prod} is the energy produced by the panel. It depends of the nature (thermal or photovoltaic) and characteristics of the panel, the irradiance on the panel, the inclination of the panel (not taken into account in the other terms), and the air temperature. Details are given in sections 2.5, 2.6 for PV and thermal panels, respectively.

H is the sensible heat flux from the solar panel to the atmosphere. We assume that the solar panel is thin, has no significant thermal mass and hence is in quasi-equilibrium. This means that the sensible heat flux, the only term that is not parameterized, is taken to be equal to the residue of the solar panel energy budget. Besides the fact that it is difficult to have a parameterization of this term, this ensures conservation of energy balance.

2.3. MODIFICATION OF THE ENERGY BALANCE OF THE ROOF

For the energy balance of the roof, the most important key parameter will, of course, be the proportion of roof area occupied by the solar panels. As mentioned above, we only consider the projection of the panels onto the horizontal surface (it would be absurd to make accurate calculations taking the inclination of the panels into account—except as noted above for production—when it is already assumed in TEB that all roofs are flat). The fraction of the roof covered by solar panels is noted f_{panel}.

The following simplifying assumptions are made:

- An average temperature is still calculated for the roof, without distinguishing between the parts of the roof under or beside the panel. This is reasonable, in particular for flat roofs with inclined panels, because the shadows cast by the panels can modify the radiative contribution to the roof beside as well as below the panels.

- The coefficient for heat transfer from the roof to the sensible heat flux is not changed (it is already in a heterogeneous environment with a roughness length of 5 cm).
- The effect of humidity on panels is neglected: the water interception reservoir treating rainwater and evaporation concerns the whole surface of the roof.
- The effect of solar panels on snow is neglected. The snow mantel, if any, accumulates uniformly on the roof. Note that snow might change the energy produced by the solar panel (but this is not taken into account yet).

These assumptions allow us to change only the radiative contributions to the energy balance of the roof. Assuming that the surface area of the shadows is equal to the surface area of the solar panels, the incoming solar radiation on the roof is:

$$SW^{\downarrow}_{roof} = (1 - f_{panel})SW^{\downarrow}_{sky} \quad (6)$$

The long-wave incoming radiation on the roof is modified by the long-wave radiation emitted downwards by the solar panels:

$$LW^{\downarrow}_{roof} = (1 - f_{panel})LW^{\downarrow}_{sky} + f_{panel}LW^{\downarrow}_{panel} \quad (7)$$

This way of implementing the interactions between solar panels and the roof below allows the considerations of the way the roof is built to be separated from the question of whether there are solar panels on it or not. For example, although it is not the case in this paper, it is possible to have greenroofs with or without solar panels. If there are solar panels, the vegetation of the greenroof will simply be more in the shade and receive slightly more infrared radiation.

2.4. RADIATIVE CHARACTERISTICS OF SOLAR PANELS

To establish the energy balance of the equivalent urban canyon, the TEB model needs the albedo (integrated between 0.4 and 2.5 μm) and the emissivity in the thermal infrared (integrated between 5 and 12 μm) for the following main areas: road, roofs, facades, glazing. The French Center for Aerospace Research (ONERA) laboratory maintains a current database of optical properties of urban materials. Specific measurements were made for emerging materials: rough white paints, photovoltaic solar panels, metal cladding, and glass (including low emissivity). The measurements for large samples of materials, e.g., for solar panels, were made using a goniometer (**Figure 2**, left).

The measurement process is fully automated in the 0.4–2.5 μm spectral domain. The position measurements acquired by the detector are regular in azimuth (0–180° range) and zenith (0–60° range) with an angular accuracy of 1°, except for the region of specular reflection, which is meshed more precisely.

The reflectance is measured with reference to a reflectance reference (Spectralon). Thereafter, the reflectance of the solar panel placed in the center of the goniometer is acquired for all recorded positions of the detector and the light source. The reference measurement is repeated at the end of the process.

The albedo of the solar panels is then computed by integrating the radiance in all directions over the entire spectral range.

FIGURE 2 | Left: Goniometer used for albedo measurements. **Right:** Instrument used for emissivity measurements.

It typically varies from 11 to 16% depending on the position of the sun and the sensor inclination. When the panel is favorably oriented relative to the sun (and hence when the incoming radiation per square meter of panel is the largest), as is usually implemented, the albedo is in the low range, and equal to about 11%.

The emissivity was measured using a SOC 400T apparatus (**Figure 2**, right). It measures the directional hemispheric reflectance for wavelengths between 2.5 and 20 μm. The resulting emissivity was 0.93 for solar panels.

2.5. ENERGY PRODUCED BY PHOTOVOLTAIC PANELS

In TEB, two different types of solar panels: thermal and photovoltaic (PV) are considered. The aim of thermal solar panels is to warm the water necessary for the occupants of the building. They are much more efficient (in terms of energy produced) than photovolatic panels, but only produce heat, not electricity.

For PV panels, the energy produced is usually parameterized as:

$$E_{PV\,prod} = Eff_{PV} \times Irr \times R(T_{panel}) \quad (W/m^2 \text{ of solar panel}) \quad (8)$$

where Eff_{PV} is the conversion efficiency of the PV panel and $R(T_{panel})$ a coefficient to reproduce the fact that solar panels are most efficient at 25°C and present a decrease in efficiency for warmer panel temperatures. The efficiency coefficient varies from 5% to 19% (Taha, 2013), with values as high as 30% possible in the far future (Nemet, 2009). In France, most PV panels use the usual crystalline silicon (xSi) technology (Leloux et al., 2012), for which the efficiency is approximately $Eff_{PV} = 14\%$. To relate the irradiance received by the panel (possibly tilted) to the incident radiation on a horizontal surface ($SW^{\downarrow}_{sky}$), it is possible either to perform geometric calculations on the relative position of the sun and panels or to apply *a priori* correction factors. This second, simpler approach is chosen here, and the coefficient of the French thermal Regulations of 2005 is used:

$$Irr = FT \times SW^{\downarrow}_{sky} \qquad (W/m^2 \text{ of solar panel}) \quad (9)$$

The correction factor FT is typically 1.11 on annual average for a South facing panel in Paris. Assuming that solar panels are placed fairly optimally, i.e., with an approximately 30° tilt and oriented between South-East and South-West (as is usually the case in

France, Leloux et al., 2012), we can estimate that the coefficient FT is equal to $FT = 1.10$ in France. The temperature dependent coefficient can be written as:

$$R(T_{panel}) = \min\left\{1;\, 1 - 0.005 \times (T_{panel} - 298.15)\right\} \quad (10)$$

Finally, the production of the PV panels is parameterized, also using the relationship between panel temperature and irradiance, as:

$$E_{PV\ prod} = Eff_{PV} \times FT \times SW^{\downarrow}_{sky} \times \min\left\{1;\, 1 - 0.005 \times (T_{air} + k_T FT \times SW^{\downarrow}_{sky} - 298.15)\right\} \quad (\mathrm{W/m^2\ of\ solar\ panel}) \quad (11)$$

2.6. ENERGY PRODUCED BY THERMAL SOLAR PANELS

The amount of energy produced by solar thermal panels is usually defined on an annual basis (Philibert, 2006). This can partly be justified by the fact that the limitation of energy production is not linked solely to the available sunlight but also to the objective in terms of quantity of water heated (there is no point in heating water beyond the set-point, typically 60°C for hot water, nor for more people than those actually occupying the building, $32l$ per person). From French regulations, for one person, the annual production with thermal solar panels is:

$$\int_{year} E_{ther\,prod} = \frac{1}{2} \times 1.16 \times 32\Delta T \quad (\mathrm{kWh/year/person}) \quad (12)$$

where ΔT is the temperature difference between cold and hot water (typically 45 K in France). The factor $\frac{1}{2}$ comes from an adjustment to account for the fact that only a part of the need for warm water can be covered by solar energy. This factor can vary depending on location, climate (frequency of presence of clouds), seasonality (less sun radiation in winter) and technical features of the installation (ADEME, 2002). A typical value of $\frac{1}{2}$ is taken here. Furthermore, it is considered that this per capita energy requirement can be satisfied by 1 m^2 of thermal panel. So, the power averaged over the year would be:

$$< E_{ther\,prod} > = \frac{1}{2} \times 1.16 \times 32\Delta T \times 1000/24/365 \quad (\mathrm{W/m^2\ of\ solar\ panel}) \quad (13)$$

Here, in order to better take the variability in production due to solar irradiation into account, instead of an annual mean computation, instantaneous production is considered in connection with the daily need for warm water. This mimics the fact that the water is heated during the day and stored until it is used during the next 24 h. So, using the regulation information above, the target energy production for 1 day can be defined as:

$$E_{ther\,target} = 1.16 \times 32\Delta T \times 1000/365 \times 3600 \quad (\mathrm{J/m^2\ of\ solar\ panel}) \quad (14)$$

The $\frac{1}{2}$ factor has disappeared here because we consider ideal heating (i.e., sunny) conditions for the definition of the target. The production of the thermal panel is then computed in three steps:

1. The instantaneous production is defined as $E_{ther\,prod} = Eff_{ther} \times Irr$ (W/m^2 of solar panel) where Eff_{ther} is the efficiency coefficient of the thermal panel and Irr the irradiance received by the panel. The efficiency of new thermal solar panels typically ranges between 0.70 and 0.80. However, in real conditions of use, especially in cities, dirt and dust on the panel reduce its energy production. Elminir et al. (2006) found a decrease of between 6% and 20% in the output power due to dust (17.4% for a 45° tilt angle of the solar panel). A similar effect of dirt had already been found by Garg (1974), with attenuation of 10–20% for tilt angles between 45° and 30°. Therefore, in the present study Eff_{ther} was set to 0.60.
2. The total amount of energy produced is summed from midnight the previous night to the current time t: $\int_{midnight}^{t} E_{ther\,prod}\mathrm{d}t$ (J/m^2 of panel).
3. If the quantity of energy produced since midnight reaches the target $E_{ther\,target}$, then any additional production during the same day is wasted and further energy production is set to zero.

To summarize, for solar thermal panels, the production is parameterized as:

$$\begin{cases} \text{if } \int_{midnight}^{t} E_{ther\,prod}\mathrm{d}t < E_{ther\,target} & \text{then } E_{ther\,prod} = Eff_{ther} \times Irr \\ \text{if } \int_{midnight}^{t} E_{ther\,prod}\mathrm{d}t = E_{ther\,target} & \text{then } E_{ther\,prod} = 0 \end{cases} \quad (15)$$

2.7. HYPOTHESES ON TYPES OF SOLAR PANELS

As the model is able to consider both thermal and PV solar panels, it is now necessary to define some hypotheses on the use of each type of panel. This is, of course, a scenario-dependent element, in the sense that it can be modified for each study. For example, Taha (2013) only studied the implementation of PV panels in the Los Angeles metropolitan area. The interest of also considering the deployment of thermal solar panels in this paper is that this energy production technology is less greenhouse gas emissive per unit of energy produced (considering its whole lifecycle) than PV (Nugent and Sovacool, 2014). Here, it will thus be supposed that both types of panels are possible. The main hypotheses are:

- On residential buildings and houses, the priority is given to thermal solar panels, which are more efficient. The thermal production is of course limited by the area of panels on the roof but it is also limited by the population in the building: it is not necessary to heat more water than required by the number of people who are going to use it. Therefore, once the necessary area of thermal solar panels is reached, the remaining space allocated for solar panels on the roof will be devoted to PV panels.

- On other types of buildings (offices, commercial, industrial, etc...) only PV panels will be installed.

The total fraction of the building's roof where solar panels (any type) can be installed is noted f_{panel} (this quantity is also scenario dependent). It is then necessary to define what proportion of the roof area is required for thermal panels, and how much area remains available for PV panels. In France, in residential buildings, the density is typically 1 occupant per 30 m^2 of floor area[1]. Furthermore, as mentioned above, 1 m^2 of thermal panel is needed per capita. This means 1 m^2 of panel per 30 m^2 of floor area. For single story accommodation, 1/30 of the roof is then equipped with thermal panels, and ($f_{panel} - 1/30$) by PV panels. If the building has two stories, thermal panels will occupy 2/30 of the roof area, and so on.

So if N_{floor} is the number of floors of the building (variable calculated in TEB), the proportions of thermal panels ($f_{ther\,panel}$) and PV panels ($f_{phot\,panel}$) are calculated as:

$$f_{ther\,panel} = \min(N_{floor}/30; f_{panel}) \quad (16)$$

$$f_{PV\,panel} = \max(f_{panel} - f_{ther\,panel}; 0) \quad (17)$$

The total production of the solar panels on the roofs can then be written:

$$E_{prod} = (f_{ther\,panel}\,E_{ther\,prod} + f_{phot\,panel}\,E_{phot\,prod})/f_{panel} \quad (W/m^2 \text{ of solar panel}) \quad (18)$$

This is this quantity that is involved in the energy balance of the panel (section 2.2).

3. IMPACT OF SOLAR PANELS ON PARIS URBAN HEAT ISLAND

3.1. SIMULATION CONFIGURATION AND SCENARIOS

We are now able to simulate the impact of the implantation of solar panels in a city on the UHI. The simulations are performed on the Paris metropolitan area, with TEB, coupled with the vegetation scheme ISBA (Noilhan and Planton, 1989) for rural areas, within the SURFEX modeling software (Masson et al., 2013b). The simulation domain is 100 km by 100 km, with a resolution of 1 km. At such a resolution, only the main characteristics of the buildings within the blocks in the grid mesh are kept. Geometric parameters are averaged in order to conserve the surface areas (for walls, roofs, gardens, roads, water, rural areas), while a majority rule applies for the architectural characteristics of buildings (age, materials, equipment) and the use to which they are put (residential, offices, commercial or industrial). These urban data are provided by a database at 250 m resolution (Figure 3 of Masson et al., 2014), which contains block types as well as 60 urban indicators. Some parameters needed by TEB, such as albedos, thermal characteristics or equipment within buildings, are deduced for each 1-km-by-1-km grid mesh from urban block types and from the use and age of the majority of buildings. Countryside parameters, such as land use and vegetation characteristics are deduced from the ecoclimap database at 1 km resolution (Masson et al., 2003). The methodology presented in Masson et al. (2014), based on a simplified Urban Boundary Layer generator (Bueno et al., 2013; Le Bras, 2014) is chosen, in order to be able to perform a simulation over an entire year. The chosen year of study is 2003, because it demonstrates the impact the solar panels would have during a heat wave.

Some hypotheses have to be made on the proportions of roofs equipped with solar panels. Hypotheses similar to those presented as "reasonably high deployment" in Taha (2013) are taken. On sloping roofs, typically on domestic houses but also old Hausmannian buildings in the historical core of Paris, $\frac{3}{4}$ of the part of the roof oriented between South-East and South-West (after Leloux et al., 2012) is assumed to be covered by solar panels (thermal or PV, or a mix of the two). This corresponds to approximately 19% of the roof being covered. On flat roofs, however, more space is available, and solar panels are taken to be installed on 50% of each roof.

Current albedos of roofing prior to the implementation of solar panels are estimated for each type of building from an architectural analysis. Historical Hausmannian buildings in the very center of Paris are roofed with zinc on top of wood, so their albedo is very high, set to 0.6. In this regard, the solar panels, even maybe thermal ones, would decrease the albedo of the city there, and might tend to increase the UHI. However, only a small proportion of this type of buildings is eligible for solar panels (19% of roofs in our hypothesis), and the spatial coverage of this type of old city blocks is limited (see Figure 3 of Masson et al., 2014). Except for the most recent industrial buildings (built after 1975), for which roof albedo is 0.5 and which, again do not cover a significant part of the metropolitan area, roof albedo for most buildings is estimated as 0.2 (e.g., tiles for houses and old industrial buildings or gray concrete roofs for collective buildings). Therefore, the impact of solar panels on historical or industrial buildings is probably counterbalanced by the other parts of the urban area, where solar panels will probably reduce the amount of solar radiation absorbed by the buildings (due to the reflection and conversion into energy by the solar panels).

Two simulations are run: one is the reference simulation corresponding to Paris in its actual state (without many solar panels) and the second is the one with the reasonably high deployment of solar panels. A comparison of the two simulations will assess the effect of the solar panels on the urban area.

3.2. RESULTS FOR ENERGY PRODUCTION AND CONSUMPTION

The impacts of solar panels are discussed in terms of energy production, of course, but also impact on energy consumption and, in the next section, on the UHI and thermal comfort. At the city scale, the production by thermal solar panels is larger than by PV. This comes both from the fact that their deployment is favored for domestic buildings and from their much higher efficiency (the former being linked to the latter). It should nevertheless be noted that, from April to August, production by thermal solar

[1] http://www.insee.fr/fr/themes/document.asp?ref_id=ip1396

panels saturates (enough hot water is produced), so their real efficiency decreases. Over the entire year, on average for the whole city, the thermal solar panels would produce approximately 265 MJ/year/m^2 of building and the PV panels 113 MJ/year/m^2 of building. This would cover an equivalent of 28% of the energy consumption for domestic heating and air-conditioning.

The solar panels also slightly modify the energy consumption of the buildings. During winter, the solar panels could induce a decrease of the energy consumption due to more infra-red energy reaching the roof, or increase it by reducing the amount of solar radiation received or by their effect on the UHI. Overall, the domestic heating demand increases by 3% per year in our scenario. During summer the need for air-conditioning will probably decrease, thanks to the shading of the roofs and the cooling induced in the urban climate (see below). The comparison between the two simulations indicates that the air-conditioning energy demand decreases by 12%. Because the energy consumption for air-conditioning is low compared to that for domestic heating, the balance between the loss in energy in winter and the gain in summer induces an increase of total energy consumption by buildings of 1%. However, in the future, when climate warming induces milder winters and hotter summers, insulation will (hopefully) be better and air-conditioning equipment, currently not widely installed in France, will (probably) take on greater importance so this balance may change. Then, massive installation of solar panels may even be beneficial for energy consumption.

3.3. RESULTS ON URBAN HEAT ISLAND

The deployment of solar panels in the Paris metropolitan area would not be neutral in terms of urban climate. **Figure 3** presents the difference in the daily minimum and maximum air temperature between the two simulations (for two contrasting months: January and August). In wintertime, when the sun is low, the impact of the solar panels on the air temperature is relatively small. Their implementation reduces the maximum air temperature by approximately 0.05 K in the city center and the UHI by more than 0.1 K in Paris and its dense suburbs, and by 0.05 K on the whole metropolitan area. However, we have seen that this is large enough to have a noticeable (if limited) influence on energy consumption for domestic heating.

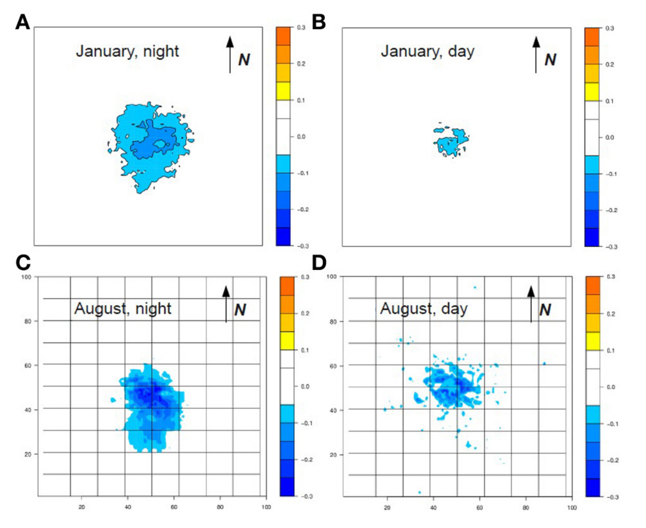


FIGURE 3 | Difference of minimum or maximum air temperature between simulations with and without solar panels. Each panel **(A–D)** is a monthly average. Horizontal and vertical axes are in km.

During the month of August, in the first half of which the famous 2003 heat wave occurred, the impacts of solar panels on air temperature would be larger. In daytime, the presence of solar panels would decrease the air temperature by more than 0.2 K, especially in the dense suburbs, where the density of solar panels is the highest, due to both the high density of building and the fact that unlike the Haussmanian buildings of the city center, the suburban apartment and commercial buildings are flat roofed. This cooling value is consistent with, even though larger than, the value of 0.05 K found for the July 2005 heat wave episode in the Los Angeles area reported by Taha (2013) for present PV panels. When the efficiency of PV panels is improved (up to 30%), Taha (2013) predicts that the cooling will reach 0.15 K. There are two possible explanations for the fact that more intense cooling is simulated for Paris. First, the presence of the sea breeze in Los Angeles could limit local cooling due to solar panels in the city while extending the area of cooling by advection of the (slightly) cooler air. This can explain why a large portion of the metropolitan area of Los Angeles is impacted by the solar panels in these simulations. Second, only PV panels were simulated by Taha (2013). The efficiency of these panels was assumed to be relatively high (20%), larger than the value used in the present study, but much smaller than the efficiency of thermal solar panels (60%). As we investigate a scenario with deployment of both types of solar panels here, the absorption of energy is larger than for PV alone.

At night, the impact of the solar panels is quite strong, even larger than during daytime, with cooling reaching 0.3 K. To the authors' knowledge, this effect is not investigated in the literature. This increased cooling at night is due to a combination of several urban micro-climate processes. First, the heat storage within the buildings is reduced in presence of solar panels, especially thermal ones, because they intercept the solar radiation. The implementation of solar panels as a separate element of the urban surface energy balance system, as done here, allows a fine description of their impact on the underlying building energetics. Second, at night, the urban boundary layer is much thinner than during the day (typically 200 m high instead of 1500 m high in summer). So any modification of the surface energy balance will have up to 10 times more influence on the air temperature at night. Such a counter-intuitive phenomenon was found by DeMunck et al. (2013b) for air-conditioning, which was shown to have more impact at night than in the day (although the heat release itself was, of course, larger in daytime). Here too, while the solar panels primarily modify the daytime processes (by absorption and transformation of the solar radiation into thermal or electrical energy), the influence on air temperature is larger at night, due to the urban fabric and the boundary layer structure.

This cooling effect, though relatively small, can improve the thermal comfort of the inhabitants. For example, it reduces the number of people exposed to any given intensity (e.g., 2 K) of the

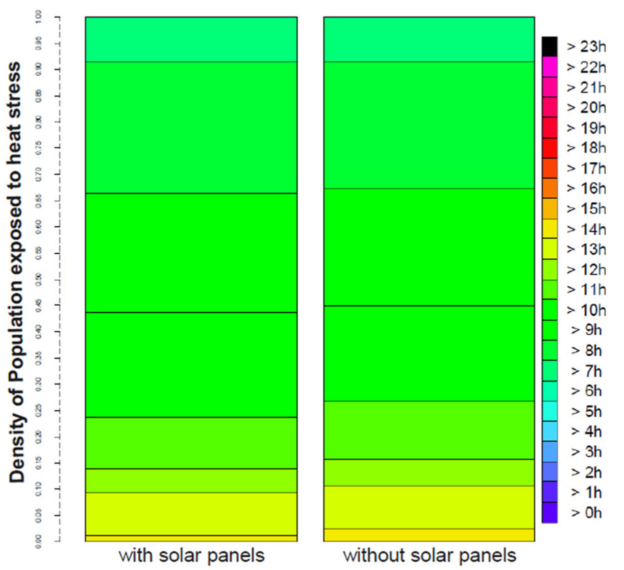


FIGURE 4 | Population exposed to moderate heat stress in August 2003 (monthly average). Left: with solar panels. **Right:** without solar panels. The figure reads this way: 100% of the population is affected by at least 7 h of heat stress per day, but only a few percents (in yellow) by more than 14 h of heat stress per day.

UHI by 4% (±0.5%) of the total population of the metropolitan area. The thermal comfort can also be evaluated by considering more environmental parameters, such as the wind, radiation and humidity, that all have an influence on human physiology. The Universal Thermal Climate Index, UTCI (www.utci.org/), is such an indicator. **Figure 4** shows the proportion of the population of the urban area that is under moderate heat stress when outside (in shade). It displays the number of hours per day that a person spends in this or any stronger level of stress. Solar panels, probably by their effect of temperature, decrease the level on thermal stress of the population. For example, while 17% of the total population is affected by heat stress for more than half a day (12 h) in the present city, the implementation of solar panels would reduce this number to 13%. While this difference seems small, it still represents a large number of people. On average, approximately 15 min of comfort is gained for outdoor conditions. This slight improvement in exposure to heat stress, although unplanned (solar panels are primarily implemented for energy production), can add to larger ones, specifically aimed at urban climate cooling, such as greening of the city.

4. DISCUSSION

Solar panels absorb solar energy to produce energy usable in buildings, either directly in the form of heat (typically to warm water) or as electricity. However, in doing so, they modify the energy balance of the urban surface in contact with the atmosphere, and so possibly influence the urban micro-climate. They also change the radiation received by the roof, and hence the building energy balance. The present paper presents a way to include solar panels in the TEB scheme. This parameterization simulates their production in a relatively precise way, as it depends on the evolving meteorological conditions, rather than simply using a rule of thumb annual production as is often done in building design. The panels also influence the building energetics and the heat fluxes (radiative and convective) to the atmosphere. Thus, it is possible to evaluate the influence of solar panels implementation strategies on the UHI.

A scenario of large but realistic deployment of solar panels in the Paris metropolitan area has been simulated. A comparison with the reference, present-day city without (many) solar panels, enables the impact of this scenario to be estimated. Unlike work previously reported in the literature, the present study implemented both thermal and PV solar panels in the model. This allowed realistic scenarios to be simulated, where thermal panels are introduced first. It is shown that solar panels, by shading of the roof, slightly increase the need for domestic heating (3%). With future improvements in insulation, this impact will probably be less significant. In summer, however, the solar panels reduce the energy needed for air-conditioning (by 12%), thanks to the shading of the roof. They also lead to a reduction of the UHI.

During summer, when sunlight is strong, the deployment of solar panels can reduce the temperature by 0.2 K. At night, a simplistic analysis would suggest that the solar panels have no effect (as there is no sunlight). However, the physical simulation performed here shows that the presence of solar panels leads to a mitigation of up to 0.3 K of the UHI at night (so more than during the day). This counter-intuitive result is due to the interaction between the urban surface energy balance (the evolution of which has been modified by solar panels) and the night-time structure of the atmospheric layer above the city. These impacts are larger than those found in previous works, because of the use of thermal panels (that are more efficient than PV panels) and due to the geographical position of Paris, which is relatively far from the sea. This means that it is not influenced by sea breezes, and hence that its UHI is stronger than for a coastal city of the same size. But it also means that local adaptation strategies aiming at decreasing the UHI will have more potent effects.

In addition to these theoretical results, some practical issues have to be taken into consideration in order to better inform decision makers. Installing PV panels or thermal solar collectors on roofs of existing buildings will change the visual appearance of the urban areas concerned. This change may be a difficult issue in towns like Paris, where the tourist industry is important, and installation will probably not be accepted on all potential surfaces. Moreover, the outdoor urban environment is highly polluted and dirt deposits on panel and collector surfaces will inevitably decrease the effectiveness of solar equipment. Regular cleaning could be a way to limit this impact but the consequences of this maintenance activity need to be evaluated (e.g., access paths, security equipment, manpower). Fire risk may also be an issue for PV panels: a series of cases were recorded for newly equipped buildings in Europe in 2013. The products implicated were withdrawn from the market but this situation calls for a rigorous selection of products and contractors as well as for a maintenance plan of the installations. The above mentioned issues require further investigation in the perspective of an economic evaluation taking both positive and negative externalities into account.

To sum up, the deployment of solar panels is good both for producing energy (and hence contributing to a decrease of greenhouse gas emissions) and for decreasing the UHI, especially in summer, when it can be a threat to health. In future climate conditions, solar panels would also help to decrease the demand of air-conditioning. Future work will focus on studying urban adaptation strategies in the long term (as far as the end of the twenty-first century) taking a large panel of possible planning options into consideration, such as city greening, improved insulation, changes in occupants' behavior, different forms of urban expansion and the deployment of renewable energy systems.

FUNDING

This work has received support from the French National Research Agency for the MUSCADE project (reference ANR-09-VILL-0003) and from the thematic advanced research network on Aeronautics and Space for the ACCLIMAT project (RTRA STAE—ACCLIMAT).

ACKNOWLEDGMENT

The authors thank Colette Marchadier for her work in the MUSCADE and ACCLIMAT projects' management.

REFERENCES

ADEME. (2002). "Eau chaude solaire - manuel pour la conception, le dimensionnement et la réalisation des installations collectives," in *Technical Report, Agence de l'Environnement et de la Maîtrise de l'Energie in French*, 110.

Arnette, A. N. (2013). Integrating rooftop solar into a multi-source energy planning optimization model. *Appl. Energ.* 111, 456–467. doi: 10.1016/j.apenergy.2013.05.003

Bueno, B., Hidalgo, J., Pigeon, G., Norford, L., and Masson, V. (2013). Calculation of air temperatures above the urban canopy layer from measurements at a rural operational weather station. *J. Appl. Meteorol. Climatol.* 52, 472–483. doi: 10.1175/JAMC-D-12-083.1

Bueno, B., Pigeon, G., Norford, L. K., Zibouche, K., and Marchadier, C. (2012). Development and evaluation of a building energy model integrated in the TEB scheme. *Geosci. Model Dev.* 5, 433–448. doi: 10.5194/gmd-5-433-2012

DeMunck, C. S., Lemonsu, A., Bouzouidja, R., Masson, V., and Claverie, R. (2013a). The greenroof module (v7.3) for modelling green roof hydrological and energetic performances within TEB. *Geosci. Model Dev.* 6, 1941–1960. doi: 10.5194/gmd-6-1941-2013

DeMunck, C. S., Pigeon, G., Masson, V., Meunier, F., Bousquet, P., Tréméac, B., et al. (2013b). How much air conditioning can increase air temperatures for a city like Paris (France)? *Int. J. Climatol.* 33, 210–227. doi: 10.1002/joc.3415

Elliott, D. (2000). Renewable energy and sustainable futures. *Futures* 32, 261–2747. doi: 10.1016/S0016-3287(99)00096-8

Elminir, H. K., Ghitas, A. E., Hamid, R. H., El-Hussainy, F., Beheary, M. M., and Abdel-Moneim, K. M. (2006). Effect of dust on the transparent cover of solar collectors. *Energ. Conver. Manag.* 47, 3192–3203. doi: 10.1016/j.enconman.2006.02.014

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guillenneuc-Jouyaux, C., et al. (2006). Excess mortality related to the August 2003 heat wave in France. *Int. Arch. Occup. Environ. Health* 80, 16–24. doi: 10.1007/s00420-006-0089-4

Gago, E. J., Roldan, J., Pacheco-Torres, R., and Ordonez, J. (2013). The city and urban heat islands: a review of strategies to mitigate adverse effects. *Renew. Sust. Energ. Rev.* 25, 749–758. doi: 10.1016/j.rser.2013.05.057

Garg, H. P. (1974). Effect of dirt on transparent covers in flat-plate solar energy collectors. *Solar Energ.* 15, 299–302. doi: 10.1016/0038-092X(74)90019-X

Gross, R., Leach, M., and Bauen, A. (2003). Progress in renewable energy. *Environ. Int.* 29, 105–122. doi: 10.1016/S0160-4120(02)00130-7

Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., et al. (2014). Environmental impacts of utility-scale solar energy. *Renew. Sust. Energ. Rev.* 29, 766–779. doi: 10.1016/j.rser.2013.08.041

Jader-Waldau, A. (2007). Photovoltaics and renewable energies in Europe. *Renew. Sust. Energ. Rev.* 11, 1414–1437. doi: 10.1016/j.rser.2005.11.001

Le Bras, J. (2014). "Fast urban heat island model for thermal comfort studies," in *11th Symposium on the Urban Environment* (Atlanta, CA: American Meteorological Society).

Leloux, J., Narvarte, L., and Trebosc, D. (2012). Review of the performance of residential PV systems in France. *Renew. Sust. Energy. Rev.* 16, 1369–1376. doi: 10.1016/j.rser.2011.07.145

Lemonsu, A., Kounkou-Arnaud, R., Desplat, J., Salagnac, J.-L., and Masson, V. (2013). Evolution of the Parisian urban climate under a global changing climate. *Clim. Change* 116, 679–692. doi: 10.1007/s10584-012-0521-6

Lemonsu, A., Masson, V., Shashua-Bar, L., Erell, E., and Pearlmutter, D. (2012). Inclusion of vegetation in the town energy balance model for modeling urban green areas. *Geosci. Model Dev.* 5, 1377–1393. doi: 10.5194/gmdd-5-1295-2012

Lund, H. (2007). Renewable energy strategies for sustainable development. *Energy* 32, 912–919. doi: 10.1016/j.energy.2006.10.017

Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models. *Bound. Layer Meteorol.* 94, 357–397. doi: 10.1023/A:1002463829265

Masson, V., Champeaux, J.-L., Chauvin, F., Meriguet, C., and Lacaze, R. (2003). A global database of land surface parameters at 1-km resolution in meteorological and climate models. *J. Clim.* 16, 1261–1282. doi: 10.1175/1520-0442-16.9.1261

Masson, V., LeMoigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., et al. (2013b). The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geosci. Model Dev.* 6, 929–960. doi: 10.5194/gmd-6-929-2013

Masson, V., Lion, Y., Peter, A., Pigeon, G., Buyck, J., and Brun, E. (2013). Grand Paris: regional landscape change to adapt city to climate warming. *Clim. Change* 117, 769–782. doi: 10.1007/s10584-012-0579-1

Masson, V., Marchadier, C., Adolphe, L., Aguejdad, R., Avner, P., Bonhomme, M., et al. (2014). Adapting cities to climate change: a systemic modelling approach. *Urban Climate.* doi: 10.1016/j.uclim.2014.03.004

Nemet, G. F. (2009). Net radiative forcing from widespread deployment of photovoltaics. *Environ. Sci. Technol.* 43, 2173–2178. doi: 10.1021/es801747c

Noilhan, J., and Planton, S. (1989). A simple parameterization of land surface processes for meteorological models. *Mon. Wea. Rev.* 117, 536–549. doi: 10.1175/1520-0493(1989)117<0536:ASPOLS>2.0.CO;2

Nugent, D., and Sovacool, B. K. (2014). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta- survey. *Energ. Pol.* 65, 229–244. doi: 10.1016/j.enpol.2013.10.048

Philibert, C. (2006). "Barriers to technology diffusion: the case of solar thermal technologies," in *Technical report, International Energy Agency, Organisation for Economic Cooperation and Development*. Available online at: http://www.iea.org/publications/freepublications/publication/Solar_Thermal.pdf

Pigeon, G., Zibouche, K., Bueno, B., Le Bras, J., and Masson, V. (2014). Evaluation of building energy simulations with the TEB model against energyplus for a set of representative buildings in Paris. *Build. Environ.* 76, 1–14. doi: 10.1016/j.enbuild.2013.10.038

Porfiriev, B. (2014). Evaluation of human losses from disasters: the case of the 2010 heat waves and forest fires in Russia. *Int. J. Disast. Risk Reduct.* 7, 91–99. doi: 10.1016/j.ijdrr.2013.12.007

Santamouris, M., Synnefa, A., and Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energ.* 85, 3085–3102. doi: 10.1016/j.solener.2010.12.023

Scherba, A., Sailor, D. J., Rosenstiel, T. N., and Wamser, C. C. (2011). Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Build. Environ.* 46, 2542–2551. doi: 10.1016/j.buildenv.2011.06.012

Sims, R. E. H., Rogner, H.-H., and Gregory, K. (2003). Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energ. Pol.* 31, 1315–1326. doi: 10.1016/S0301-4215(02)00192-1

Sovacool, B. K., and Ratan, P. L. (2012). Conceptualizing the acceptance of wind and solar electricity. *Renew. Sust. Energ. Rev.* 16, 5268–5279. doi: 10.1016/j.rser.2012.04.048

Taha, H. (2013). The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas. *Solar Energ.* 91, 358–367. doi: 10.1016/j.solener.2012.09.014

Traisnel, J. P., Maizia, M., and Roditi, D. (2004). Habitat et développement durable: Les perspectives offertes par le solaire thermique. *Les cahiers du club d'ingénérie prospective énérgie et environnement* 16, 3–46 (in French).

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 04 March 2014; paper pending published: 31 March 2014; accepted: 29 April 2014; published online: 04 June 2014.

Citation: Masson V, Bonhomme M, Salagnac J-L, Briottet X and Lemonsu A (2014) Solar panels reduce both global warming and urban heat island. Front. Environ. Sci. ***2****:14. doi: 10.3389/fenvs.2014.00014*

This article was submitted to Atmospheric Sciences, a section of the journal Frontiers in Environmental Science.

The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures (Open access: http://www.nature.com/articles/srep35070)

Article *in* Scientific Reports · November 2016

DOI: 10.1038/srep35070

5 authors, including:


Greg Barron-Gafford
The University of Arizona


Rebecca Larkin Minor
The University of Arizona


Mitchell Pavao-Zuckerman
University of Maryland, College Park

SCIENTIFIC REPORTS

OPEN

The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures

Received: 26 May 2016
Accepted: 23 September 2016
Published: 13 October 2016

Greg A. Barron-Gafford[1,2], Rebecca L. Minor[1,2], Nathan A. Allen[3], Alex D. Cronin[4], Adria E. Brooks[5] & Mitchell A. Pavao-Zuckerman[6]

While photovoltaic (PV) renewable energy production has surged, concerns remain about whether or not PV power plants induce a "heat island" (PVHI) effect, much like the increase in ambient temperatures relative to wildlands generates an Urban Heat Island effect in cities. Transitions to PV plants alter the way that incoming energy is reflected back to the atmosphere or absorbed, stored, and reradiated because PV plants change the albedo, vegetation, and structure of the terrain. Prior work on the PVHI has been mostly theoretical or based upon simulated models. Furthermore, past empirical work has been limited in scope to a single biome. Because there are still large uncertainties surrounding the potential for a PHVI effect, we examined the PVHI empirically with experiments that spanned three biomes. We found temperatures over a PV plant were regularly 3–4 °C warmer than wildlands at night, which is in direct contrast to other studies based on models that suggested that PV systems should decrease ambient temperatures. Deducing the underlying cause and scale of the PVHI effect and identifying mitigation strategies are key in supporting decision-making regarding PV development, particularly in semiarid landscapes, which are among the most likely for large-scale PV installations.

Electricity production from large-scale photovoltaic (PV) installations has increased exponentially in recent decades[1–3]. This proliferation in renewable energy portfolios and PV powerplants demonstrate an increase in the acceptance and cost-effectiveness of this technology[4,5]. Corresponding with this upsurge in installation has been an increase in the assessment of the impacts of utility-scale PV[4,6–8], including those on the efficacy of PV to offset energy needs[9,10]. A growing concern that remains understudied is whether or not PV installations cause a "heat island" (PVHI) effect that warms surrounding areas, thereby potentially influencing wildlife habitat, ecosystem function in wildlands, and human health and even home values in residential areas[11]. As with the Urban Heat Island (UHI) effect, large PV power plants induce a landscape change that reduces albedo so that the modified landscape is darker and, therefore, less reflective. Lowering the terrestrial albedo from ~20% in natural deserts[12] to ~5% over PV panels[13] alters the energy balance of absorption, storage, and release of short- and longwave radiation[14,15]. However, several differences between the UHI and potential PVHI effects confound a simple comparison and produce competing hypotheses about whether or not large-scale PV installations will create a heat island effect. These include: (*i*) PV installations shade a portion of the ground and therefore could reduce heat absorption in surface soils[16], (*ii*) PV panels are thin and have little heat capacity per unit area but PV modules emit thermal radiation both up and down, and this is particularly significant during the day when PV modules are often 20 °C warmer than ambient temperatures, (*iii*) vegetation is usually removed from PV power plants, reducing the amount of cooling due to transpiration[14], (*iv*) electric power removes energy from PV power plants, and (*v*) PV panels reflect and absorb upwelling longwave radiation, and thus can prevent the soil from cooling as much as it might under a dark sky at night.

Public concerns over a PVHI effect have, in some cases, led to resistance to large-scale solar development. By some estimates, nearly half of recently proposed energy projects have been delayed or abandoned due to local opposition[11]. Yet, there is a remarkable lack of data as to whether or not the PVHI effect is real or simply an issue

[1]School of Geography & Development, University of Arizona, Tucson, AZ, USA. [2]Office of Research & Development; College of Science, Biosphere 2, University of Arizona, Tucson, AZ, USA. [3]Nevada Center of Excellence, Desert Research Institute, Las Vegas, NV, USA. [4]Department of Physics, University of Arizona, Tucson, AZ, USA. [5]Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, WI, USA. [6]Department of Environmental Science & Technology, University of Maryland, College Park, MD, USA. Correspondence and requests for materials should be addressed to G.A.B.-G. (email: gregbg@email.arizona.edu)

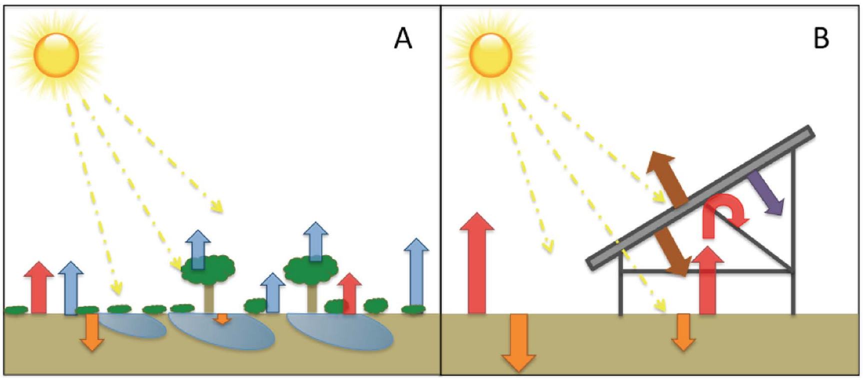


Figure 1. Illustration of midday energy exchange. Assuming equal rates of incoming energy from the sun, a transition from (**A**) a vegetated ecosystem to (**B**) a photovoltaic (PV) power plant installation will significantly alter the energy flux dynamics of the area. Within natural ecosystems, vegetation reduces heat capture and storage in soils (orange arrows), and infiltrated water and vegetation release heat-dissipating latent energy fluxes in the transition of water-to-water vapor to the atmosphere through evapotranspiration (blue arrows). These latent heat fluxes are dramatically reduced in typical PV installations, leading to greater sensible heat fluxes (red arrows). Energy re-radiation from PV panels (brown arrow) and energy transferred to electricity (purple arrow) are also shown.

associated with perceptions of environmental change caused by the installations that lead to "not in my backyard" (NIMBY) thinking. Some models have suggested that PV systems can actually cause a cooling effect on the local environment, depending on the efficiency and placement of the PV panels[17,18]. But these studies are limited in their applicability when evaluating large-scale PV installations because they consider changes in albedo and energy exchange within an urban environment (rather than a natural ecosystem) or in European locations that are not representative of semiarid energy dynamics where large-scale PV installations are concentrated[10,19]. Most previous research, then, is based on untested theory and numerical modeling. Therefore, the potential for a PHVI effect must be examined with empirical data obtained through rigorous experimental terms.

The significance of a PVHI effect depends on energy balance. Incoming solar energy typically is either reflected back to the atmosphere or absorbed, stored, and later re-radiated in the form of latent or sensible heat (Fig. 1)[20,21]. Within natural ecosystems, vegetation reduces heat gain and storage in soils by creating surface shading, though the degree of shading varies among plant types[22]. Energy absorbed by vegetation and surface soils can be released as latent heat in the transition of liquid water to water vapor to the atmosphere through evapotranspiration – the combined water loss from soils (evaporation) and vegetation (transpiration). This heat-dissipating latent energy exchange is dramatically reduced in a typical PV installation (Fig. 1 transition from A-to-B), potentially leading to greater heat absorption by soils in PV installations. This increased absorption, in turn, could increase soil temperatures and lead to greater sensible heat efflux from the soil in the form of radiation and convection. Additionally, PV panel surfaces absorb more solar insolation due to a decreased albedo[13,23,24]. PV panels will re-radiate most of this energy as longwave sensible heat and convert a lesser amount (~20%) of this energy into usable electricity. PV panels also allow some light energy to pass, which, again, in unvegetated soils will lead to greater heat absorption. This increased absorption could lead to greater sensible heat efflux from the soil that may be trapped under the PV panels. A PVHI effect would be the result of a detectable increase in sensible heat flux (atmospheric warming) resulting from an alteration in the balance of incoming and outgoing energy fluxes due to landscape transformation. Developing a full thermal model is challenging[17,18,25], and there are large uncertainties surrounding multiple terms including variations in albedo, cloud cover, seasonality in advection, and panel efficiency, which itself is dynamic and impacted by the local environment. These uncertainties are compounded by the lack of empirical data.

We addressed the paucity of direct quantification of a PVHI effect by simultaneously monitoring three sites that represent a natural desert ecosystem, the traditional built environment (parking lot surrounded by commercial buildings), and a PV power plant. We define a PVHI effect as the difference in ambient air temperature between the PV power plant and the desert landscape. Similarly, UHI is defined as the difference in temperature between the built environment and the desert. We reduced confounding effects of variability in local incoming energy, temperature, and precipitation by utilizing sites contained within a 1 km area.

At each site, we monitored air temperature continuously for over one year using aspirated temperature probes 2.5 m above the soil surface. Average annual temperature was 22.7 + 0.5 °C in the PV installation, while the nearby desert ecosystem was only 20.3 + 0.5 °C, indicating a PVHI effect. Temperature differences between areas varied significantly depending on time of day and month of the year (Fig. 2), but the PV installation was always greater than or equal in temperature to other sites. As is the case with the UHI effect in dryland regions, the PVHI effect delayed the cooling of ambient temperatures in the evening, yielding the most significant difference in overnight temperatures across all seasons. Annual average midnight temperatures were 19.3 + 0.6 °C in the PV installation, while the nearby desert ecosystem was only 15.8 + 0.6 °C. This PVHI effect was more significant in terms of actual degrees of warming (+3.5 °C) in warm months (Spring and Summer; Fig. 3, right).

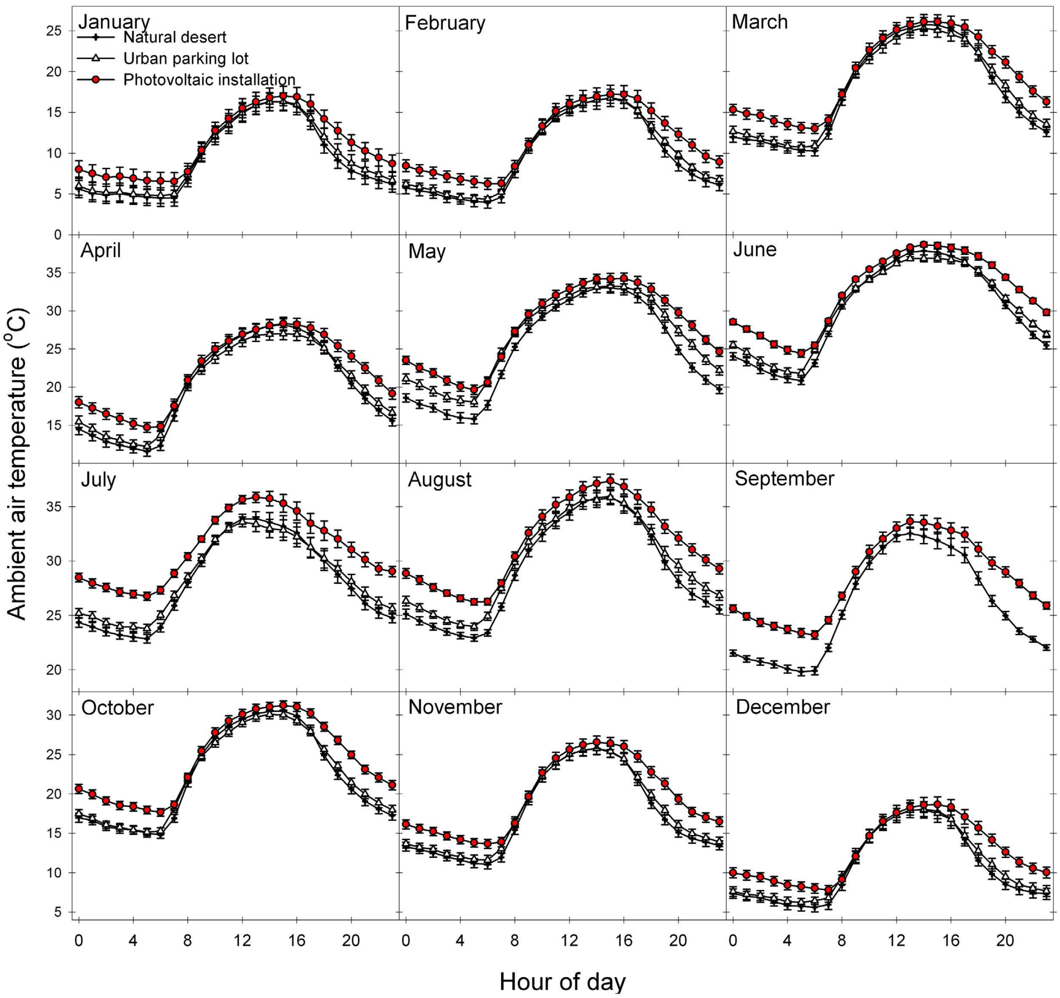


Figure 2. Average monthly ambient temperatures throughout a 24-hour period provide evidence of a photovoltaic heat island (PVHI) effect.

In both PVHI and UHI scenarios, the greater amount of exposed ground surfaces compared to natural systems absorbs a larger proportion of high-energy, shortwave solar radiation during the day. Combined with minimal rates of heat-dissipating transpiration from vegetation, a proportionally higher amount of stored energy is reradiated as longwave radiation during the night in the form of sensible heat (Fig. 1)[15]. Because PV installations introduce shading with a material that, itself, should not store much incoming radiation, one might hypothesize that the effect of a PVHI effect would be lesser than that of a UHI. Here, we found that the difference in evening ambient air temperature was consistently greater between the PV installation and the desert site than between the parking lot (UHI) and the desert site (Fig. 3). The PVHI effect caused ambient temperature to regularly approach or be in excess of 4 °C warmer than the natural desert in the evenings, essentially doubling the temperature increase due to UHI measured here. This more significant warming under the PVHI than the UHI may be due to heat trapping of re-radiated sensible heat flux under PV arrays at night. Daytime differences from the natural ecosystem were similar between the PV installation and urban parking lot areas, with the exception of the Spring and Summer months, when the PVHI effect was significantly greater than UHI in the day. During these warm seasons, average midnight temperatures were 25.5 + 0.5 °C in the PV installation and 23.2 + 0.5 °C in the parking lot, while the nearby desert ecosystem was only 21.4 + 0.5 °C.

The results presented here demonstrate that the PVHI effect is real and can significantly increase temperatures over PV power plant installations relative to nearby wildlands. More detailed measurements of the underlying causes of the PVHI effect, potential mitigation strategies, and the relative influence of PVHI in the context of the intrinsic carbon offsets from the use of this renewable energy are needed. Thus, we raise several new questions and highlight critical unknowns requiring future research.

What is the physical basis of land transformations that might cause a PVHI?

We hypothesize that the PVHI effect results from the effective transition in how energy moves in and out of a PV installation versus a natural ecosystem. However, measuring the individual components of an energy flux model remains a necessary task. These measurements are difficult and expensive but, nevertheless, are indispensable in identifying the relative influence of multiple potential drivers of the PVHI effect found here. Environmental

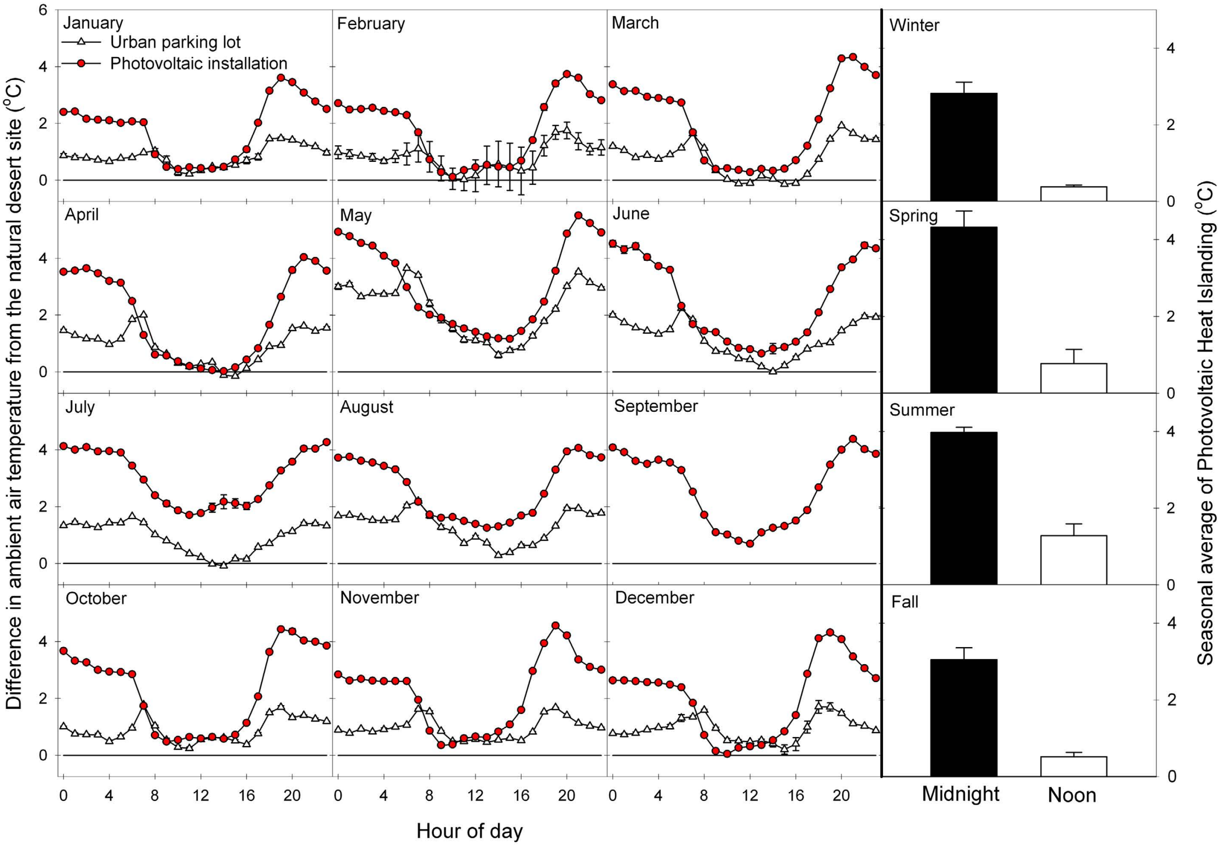


Figure 3. (Left) Average monthly levels of Photovoltaic Heat Islanding (ambient temperature difference between PV installation and desert) and Urban Heat Islanding (ambient temperature difference between the urban parking lot and the desert). (Right) Average night and day temperatures for four seasonal periods, illustrating a significant PVHI effect across all seasons, with the greatest influence on ambient temperatures at night.

conditions that determine patterns of ecosystem carbon, energy, and water dynamics are driven by the means through which incoming energy is reflected or absorbed. Because we lack fundamental knowledge of the changes in surface energy fluxes and microclimates of ecosystems undergoing this land use change, we have little ability to predict the implications in terms of carbon or water cycling[4,8].

What are the physical implications of a PVHI, and how do they vary by region?

The size of an UHI is determined by properties of the city, including total population[26–28], spatial extent, and the geographic location of that city[29–31]. We should, similarly, consider the spatial scale and geographic position of a PV installation when considering the presence and importance of the PVHI effect. Remote sensing could be coupled with ground-based measurements to determine the lateral and vertical extent of the PVHI effect. We could then determine if the size of the PVHI effect scales with some measure of the power plant (for example, panel density or spatial footprint) and whether or not a PVHI effect reaches surrounding areas like wildlands and neighborhoods. Given that different regions around the globe each have distinct background levels of vegetative ground cover and thermodynamic patterns of latent and sensible heat exchange, it is possible that a transition from a natural wildland to a typical PV power plant will have different outcomes than demonstrated here. The paucity in data on the physical effects of this important and growing land use and land cover change warrants more studies from representative ecosystems.

What are the human implications of a PVHI, and how might we mitigate these effects?

With the growing popularity of renewable energy production, the boundaries between residential areas and larger-scale PV installations are decreasing. In fact, closer proximity with residential areas is leading to increased calls for zoning and city planning codes for larger PV installations[32,33], and PVHI-based concerns over potential reductions in real estate value or health issues tied to Human Thermal Comfort (HTC)[34]. Mitigation of a PVHI effect through targeted revegetation could have synergistic effects in easing ecosystem degradation associated with development of a utility scale PV site and increasing the collective ecosystem services associated with an area[4]. But what are the best mitigation measures? What tradeoffs exist in terms of various means of revegetating degraded PV installations? Can other albedo modifications be used to moderate the severity of the PVHI?

Figure 4. Experimental sites. Monitoring a (1) natural semiarid desert ecosystem, (2) solar (PV) photovoltaic installation, and (3) an "urban" parking lot – the typical source of urban heat islanding – within a 1 km^2 area enabled relative control for the incoming solar energy, allowing us to quantify variation in the localized temperature of these three environments over a year-long time period. The Google Earth image shows the University of Arizona's Science and Technology Park's Solar Zone.

To fully contextualize these findings in terms of global warming, one needs to consider the relative significance of the (globally averaged) decrease in albedo due to PV power plants and their associated warming from the PVHI against the carbon dioxide emission reductions associated with PV power plants. The data presented here represents the first experimental and empirical examination of the presence of a heat island effect associated with PV power plants. An integrated approach to the physical and social dimensions of the PVHI is key in supporting decision-making regarding PV development.

Methods

Site Description. We simultaneously monitored a suite of sites that represent the traditional built urban environment (a parking lot) and the transformation from a natural system (undeveloped desert) to a 1 MW PV power plant (Fig. 4; Map data: Google). To minimize confounding effects of variability in local incoming energy, temperature, and precipitation, we identified sites within a 1 km area. All sites were within the boundaries of the University of Arizona Science and Technology Park Solar Zone (32.092150°N, 110.808764°W; elevation: 888 m ASL). Within a 200 m diameter of the semiarid desert site's environmental monitoring station, the area is composed of a sparse mix of semiarid grasses (*Sporobolus wrightii, Eragrostis lehmanniana*, and *Muhlenbergia porteri*), cacti (*Opuntia* spp. and *Ferocactus* spp.), and occasional woody shrubs including creosote bush (*Larrea tridentata*), whitethorn acacia (*Acacia constricta*), and velvet mesquite (*Prosopis velutina*). The remaining area is bare soil. These species commonly co-occur on low elevation desert bajadas, creosote bush flats, and semiarid grasslands. The photovoltaic installation was put in place in early 2011, three full years prior when we initiated monitoring at the site. We maintained the measurement installations for one full year to capture seasonal variation due to sun angle and extremes associated with hot and cold periods. Panels rest on a single-axis tracker system that pivot east-to-west throughout the day. A parking lot with associated building served as our "urban" site and is of comparable spatial scale as our PV site.

Monitoring Equipment & Variables Monitored. Ambient air temperature (°C) was measured with a shaded, aspirated temperature probe 2.5 m above the soil surface (Vaisala HMP60, Vaisala, Helsinki, Finland in the desert and Microdaq U23, Onset, Bourne, MA in the parking lot). Temperature probes were cross-validated for precision (closeness of temperature readings across all probes) at the onset of the experiment. Measurements of temperature were recorded at 30-minute intervals throughout a 24-hour day. Data were recorded on a data-logger (CR1000, Campbell Scientific, Logan, Utah or Microstation, Onset, Bourne, MA). Data from this instrument array is shown for a yearlong period from April 2014 through March 2015. Data from the parking lot was lost for September 2014 because of power supply issues with the datalogger.

Statistical analysis. Monthly averages of hourly (on-the-hour) data were used to compare across the natural semiarid desert, urban, and PV sites. A Photovoltaic Heat Island (PVHI) effect was calculated as differences in these hourly averages between the PV site and the natural desert site, and estimates of Urban Heat Island (UHI) effect was calculated as differences in hourly averages between the urban parking lot site and the natural desert site. We used midnight and noon values to examine maximum and minimum, respectively, differences in temperatures among the three measurement sites and to test for significance of heat islanding at these times. Comparisons among the sites were made using Tukey's honestly significant difference (HSD) test[35]. Standard errors to calculate HSD were made using pooled midnight and noon values across seasonal periods of winter (January-March), spring (April-June), summer (July-September), and fall (October-December). Seasonal analyses allowed us to identify variation throughout a yearlong period and relate patterns of PVHI or UHI effects with seasons of high or low average temperature to examine correlations between background environmental parameters and localized heat islanding.

References

1. IPCC. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. *Prepared by Working Group III of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011).
2. REN21. Renewables 2014 Global Status Report (Paris: REN21 Secretariat; ISBN 978-3-9815934-2-6, 2014).
3. U.S. Energy Information Administration. June 2016 Monthly Energy Review. U.S. Department of Energy. Office of Energy Statistics. Washington, DC (2016).
4. Hernandez, R. R. *et al.* Environmental impacts of utility-scale solar energy. *Renewable & Sustainable Energy Reviews* **29,** 766–779, doi: 10.1016/j.rser.2013.08.041 (2014).
5. Bazilian, M. *et al.* Re-considering the economics of photovoltaic power. *Renewable Energy* **53,** 329–338, doi: http://dx.doi.org/10.1016/j.renene.2012.11.029 (2013).
6. Dale, V. H., Efroymson, R. A. & Kline, K. L. The land use-climate change-energy nexus. *Landsc. Ecol.* **26,** 755–773, doi: 10.1007/s10980-011-9606-2 (2011).
7. Copeland, H. E., Pocewicz, A. & Kiesecker, J. M. In *Energy Development and Wildlife Conservation in Western North America* (ed Naugle, David E.) 7–22 (Springer, 2011).
8. Armstrong, A., Waldron, S., Whitaker, J. & Ostle, N. J. Wind farm and solar park effects on plant-soil carbon cycling: uncertain impacts of changes in ground-level microclimate. *Global Change Biology* **20,** 1699–1706, doi: 10.1111/gcb.12437 (2014).
9. Hernandez, R. R., Hoffacker, M. K. & Field, C. B. Efficient use of land to meet sustainable energy needs. *Nature Climate Change* **5,** 353–358, doi: 10.1038/nclimate2556 (2015).
10. Hernandez, R. R., Hoffacker, M. K. & Field, C. B. Land-Use efficiency of big solar. *Environmental Science & Technology* **48,** 1315–1323, doi: 10.1021/es4043726 (2014).
11. Pociask, S. & Fuhr, J. P. Jr. Progress Denied: A study on the potential economic impact of permitting challenges facing proposed energy projects (U.S. Chamber of Commerce, 2011).
12. Michalek, J. L. *et al.* Satellite measurements of albedo and radiant temperature from semi-desert grassland along the Arizona/Sonora border. *Climatic Change* **48,** 417–425, doi: 10.1023/a:1010769416826 (2001).
13. Burg, B. R., Ruch, P., Paredes, S. & Michel, B. Placement and efficiency effects on radiative forcing of solar installations. *11th International Conference on Ceonctrator Photovoltaic Systems* **1679**, doi: 10.1063/1.4931546 (2015).
14. Solecki, W. D. *et al.* Mitigation of the heat island effect in urban New Jersey. *Environmental Hazards* **6,** 39–49, doi: 10.1016/j.hazards.2004.12.002 (2005).
15. Oke, T. R. The energetic basis of the urban heat island (Symons Memorial Lecture, 20 May 1980). *Quarterly Journal, Royal Meteorological Society* **108,** 1–24 (1982).
16. Smith, S. D., Patten, D. T. & Monson, R. K. Effects of artificially imposed shade on a Sonoran Desert ecosystem: microclimate and vegetation. *Journal of Arid Environments* **13,** 65–82 (1987).
17. Taha, H. The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas. *Solar Energy* **91,** 358–367, doi: 10.1016/j.solener.2012.09.014 (2013).
18. Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X. & Lemonsu, A. Solar panels reduce both global warming and Urban Heat Island. *Frontiers in Environmental Science* **2,** 14, doi: 10.3389/fenvs.2014.00014 (2014).
19. Roberts, B. J. Solar production potential across the United States. *Department of Energy, National Renewable Energy Laboratory.* http://www.climatecentral.org/news/eastern-us-solar-development-18714. *19 September* (2012).
20. Monteith, J. L. & Unsworth, M. H. *Principles of Environmental Physics Third Edition* (Elsevier, San Diego, CA, USA, 1990).
21. Campbell, G. S. & Norman, J. M. *An Introduction to Eenvironmental Biophysics Second Edition* (Springer, New York, USA, 1998).
22. Breshears, D. D. The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics? *Frontiers in Ecology and the Environment* **4,** 96–104, doi: 10.1890/1540-9295(2006)004[0096:tgctie]2.0.co;2 (2006).
23. Oke, T. R. *Boundary Layer Climates. Second Edition* (Routledge New York, 1992).
24. Ahrens, C. D. *Meteorology Today. An Introduction to Weather, Climate, and the Environment Eighth Edition* (Thompson, Brooks/Cole USA 2006).
25. Fthenakis, V. & Yu, Y. Analysis of the potential for a heatisland effect in large solar farms. *Analysis of the potential for a heatisland effect in large solar farms; 2013 IEEE 39th Photovoltaic Specialists Conference* 3362–3366 (2013).
26. Santamouris, M. Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of The Total Environment* **512–513,** 582–598, doi: http://dx.doi.org/10.1016/j.scitotenv.2015.01.060 (2015).
27. Oke, T. R. City size and the urban heat island. *Atmospheric Environment* **7,** 769–779, doi: 10.1016/0004-6981(73)90140-6 (1973).
28. Wang, W.-C., Zeng, Z. & Karl, T. R. Urban heat islands in China. *Geophysical Research Letters* **17,** 2377–2380, doi: 10.1029/GL017i013p02377 (1990).
29. Nasrallah, H. A., Brazel, A. J. & Balling, R. C. Jr Analysis of the Kuwait City urban heat island. *International Journal of Climatology* **10,** 401–405 (1990).
30. Montávez, J. P., Rodríguez, A. & Jiménez, J. I. A study of the Urban Heat Island of Granada. *International Journal of Climatology* **20,** 899–911, doi: 10.1002/1097-0088(20000630)20:8<899::aid-joc433>3.0.co;2-i (2000).
31. Buyantuyev, A. & Wu, J. Urban heat islands and landscape heterogeneity: Linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. *Landsc. Ecol.* **25,** 17–33, doi: 10.1007/s10980-009-9402-4 (2010).
32. White, J. G. A Model Ordinance for Energy Projects; Oregon Department of Energy. http://www.oregon.gov/ENERGY/SITING/docs/ModelEnergyOrdinance.pdf (2005).

33. Lovelady, A. Planning and Zoning for Solar in North Carolina. *University of North Carolina at Chapel Hill, School of Government* (2014).
34. Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M. & Demuzere, M. Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. *Progress in Physical Geography* **37,** 2–28, doi: 10.1177/0309133312461032 (2013).
35. Zar, J. H. *Biostatistical analysis, Prentice-Hall, Englewood Cliffs, p 215* (1974).

Acknowledgements

The authors thank Ken Marcus for access to the University of Arizona Solar Zone and the Science and Technology Park and to Tucson Electric Power for access to their PV installation. This research was supported by the University of Arizona Institute of the Environment and the Office of Research & Development through the TRIF-funded Water, Environmental and Energy Solutions initiative.

Author Contributions

G.A.B.-G., R.L.M. and N.A.A. established research sites and installed monitoring equipment. G.A.B.-G. directed research and R.L.M. conducted most site maintenance. G.A.B.-G., N.A.A., A.D.C. and M.A.P.-Z. led efforts to secure funding for the research. All authors discussed the results and contributed to the manuscript.

Additional Information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Barron-Gafford, G. A. *et al.* The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Sci. Rep.* **6**, 35070; doi: 10.1038/srep35070 (2016).

(provided by Mr. Mueller)

Analysis of the Potential for a Heat Island Effect in Large Solar Farms

Vasilis Fthenakis[1,2] and Yuanhao Yu[1]

[1] Center for Life Cycle Analysis, Department of Earth and Environmental Engineering, Columbia University, New York, NY

[2] PV Environmental Research Center, Brookhaven National Laboratory, Upton, NY

***Abstract* — Large-scale solar power plants are being built at a rapid rate, and are setting up to use hundreds of thousands of acres of land surface. The thermal energy flows to the environment related to the operation of such facilities have not, so far, been addressed comprehensively. We are developing rigorous computational fluid dynamics (CFD) simulation capabilities for modeling the air velocity, turbulence, and energy flow fields induced by large solar PV farms to answer questions pertaining to potential impacts of solar farms on local microclimate. Using the CFD codes Ansys CFX and Fluent, we conducted detailed 3-D simulations of a 1 MW section of a solar farm in North America and compared the results with recorded wind and temperature field data from the whole solar farm. Both the field data and the simulations show that the annual average of air temperatures in the center of PV field can reach up to 1.9℃ above the ambient temperature, and that this thermal energy completely dissipates to the environment at heights of 5 to 18 m. The data also show a prompt dissipation of thermal energy with distance from the solar farm, with the air temperatures approaching (within 0.3℃) the ambient at about 300 m away of the perimeter of the solar farm. Analysis of 18 months of detailed data showed that in most days, the solar array was completely cooled at night, and, thus, it is unlikely that a heat island effect could occur. Work is in progress to approximate the flow fields in the solar farm with 2-D simulations and detail the temperature and wind profiles of the whole utility scale PV plant and the surrounding region. The results from these simulations can be extrapolated to assess potential local impacts from a number of solar farms reflecting various scenarios of large PV penetration into regional and global grids.**

***Index Terms* – PV, climate change, heat island, fluid dynamics**

I. INTRODUCTION

Solar farms in the capacity range of 50MW to 500 MW are being proliferating in North America and other parts of the world and those occupy land in the range from 275 to 4000 acres. The environmental impacts from the installation and operation phases of large solar farms deserve comprehensive research and understanding. Turney and Fthenakis [1] investigated 32 categories of impacts from the life-stages of solar farms and were able to categorize such impacts as either beneficial or neutral, with the exception of the "local climate" effects for which they concluded that research and observation are needed. PV panels convert most of the incident solar radiation into heat and can alter the air-flow and temperature profiles near the panels. Such changes, may subsequently affect the thermal environment of near-by populations of humans and other species. Nemet [2] investigated the effect on global climate due to albedo change from widespread installation of solar panels and found this to be small compared to benefits from the reduction in greenhouse gas emissions. However, Nemet did not consider local micro-climates and his analytical results have not been verified with any field data. Donovan [3] assumed that the albedo of ground-mounted PV panels is similar to that of underlying grassland and, using simple calculations, postulated that the heat island effect from installing PV on grassy land would be negligible. Yutaka [4] investigated the potential for large scale of roof-top PV installations in Tokyo to alter the heat island effect of the city and found this to be negligible if PV systems are installed on black roofs.

In our study we aim in comprehensively addressing the issue by modeling the air and energy flows around a solar farm and comparing those with measured wind and temperature data.

II. FIELD DATA DESCRIPTION AND ANALYSIS

Detailed measurements of temperature, wind speed, wind direction, solar irradiance, relative humidity, and rain fall were recorded at a large solar farm in North America. Fig. 1 shows an aerial photograph of the solar farm and the locations where the field measurements are taken.

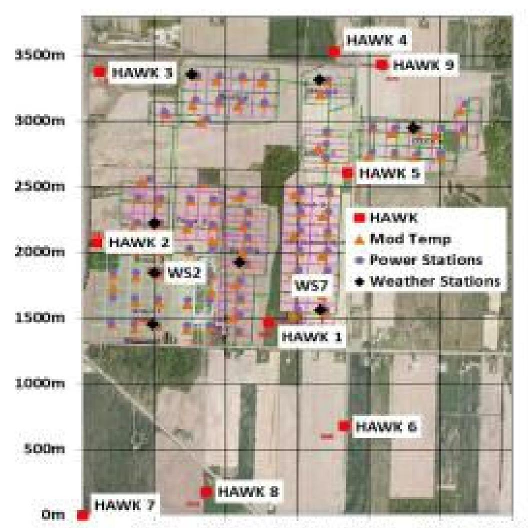


Fig. 1. A picture of the solar farm indicating the locations of the monitoring stations

The field data are obtained from 17 monitoring stations within and around the solar farm, including 8 weather stations (WS) and 9 Hawk stations (HK), all at 2.5 m heights off the ground. There also 80 module temperature (MT) sensors at the back-side of the modules close to each of the corresponding power stations. The WS and MT provide data at 1-min intervals, while the Hawk provides data every 30 minutes. The WS and MT data cover a period of one year from October 2010 to September 2011, while the Hawk data cover a period of 18 months from March 2010 through August 2011.

Hawk stations 3, 6, 7, 8 and 9 are outside the solar farm and were used as reference points indicating ambient conditions. The measurements from Hawk 3, 6, 8 and 9 agree very well confirming that their distances from the perimeter of the solar farm are sufficient for them to be unaffected by the thermal mass of the PV system; Hawk 7 shows higher temperatures likely due to a calibration inaccuracy. In our comparative data analysis we use Hawk 6 as a reference point and, since the prevailing winds are from the south, we selected the section around WS7 as the field for our CFD simulations. Figures 2 to 7 show the difference between the temperatures in Hawk 6 and those in the weather stations WS2 and WS7 within the field, and Hawks 1, 2, 4 and 5 around the solar field.

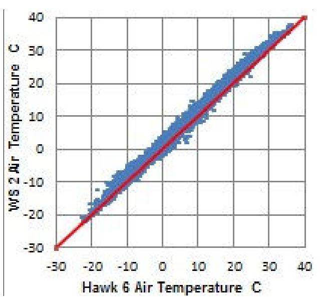


Fig. 2. Air temp WS2 vs. Hawk 6

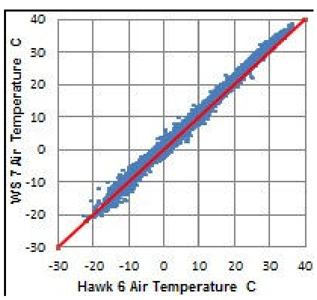


Fig.3. Air temp WS7 vs. Hawk6

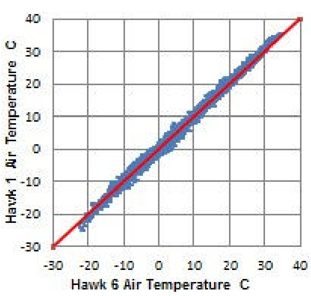


Fig. 4. Air temp Hawk 1 vs. 6

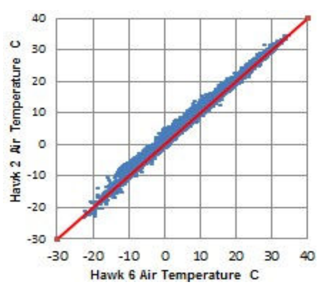


Fig. 5. Air temp Hawk 2 vs. 6

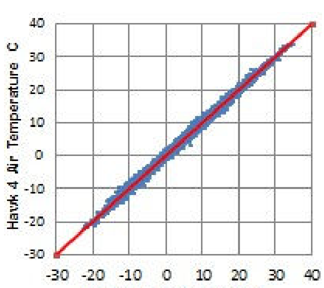


Fig. 6. Air temp Hawk 1 vs. 6

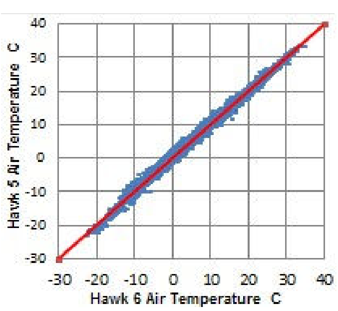


Fig. 7. Air temp Hawk 2 vs. 6

These figures and Table 1 show that with the exception of Hawk 4, the closer the proximity to solar farm the higher the temperature difference from the ambient (indicated by Hawk 6). The relative high temperatures recorded at Hawk 4, and also the relative low temperatures at Hawks 1 and 5 are explained by the prevailing wind direction, which for the time period used in our analysis (8/14/2010-3/14/2011) was Southerly (158°-202°). Hawk 4 is downwind of the solar farm, whereas Hawks 1 and 5 are upwind; the downwind station "feels" more the effect of the heat generated at the solar farm than the ones upwind.

Fig. 8 shows the decline in air temperature as a function of distance to solar farm perimeter. Distances for WS2 and WS7 are negative since they are located inside the solar farm site. WS2 is further into the solar farm and this is reflected in its higher temperature difference than WS7.

TABLE I
DIFFERENCE OF AIR TEMPERATURE (@2.5 M HEIGHTS) BETWEEN THE LISTED WEATHER AND HAWK STATIONS AND THE AMBIENT

Met Station	WS2	WS7	HK1	HK2	HK3	HK4	HK5	HK9
Temp Difference from H6 (^{o}C)	1.878	1.468	0.488	1.292	0.292	0.609	0.664	0.289
Distance to solar farm perimeter (m)	-440	-100	100	10	450	210	20	300

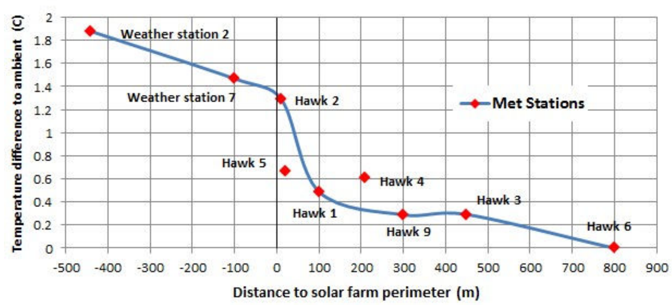


Fig. 8. Air temperature difference as a function of distance from the perimeter of the solar farm. Negative distances indicate locations within the solar farm.

We also examined in detail the temperature differences between the modules and the surrounding air. These vary throughout the year but the module temperatures are consistently higher than those of the surrounding air during the day, whereas at night the modules cool to temperatures below ambient; an example is shown in Fig. 9. Thus, this PV solar farm did not induce a day-after-day increase in ambient temperature, and therefore, adverse micro-climate changes from a potential PV plant are not a concern.

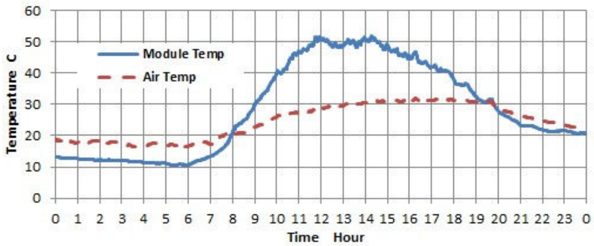


Fig. 9. Comparison of module temperature and air temperature 2.5 m off the ground on a sunny day (July 1, 2011)

III. CFD Model Development

In preliminary simulations we tested the Ansys CFX and FLUENT computational fluid dynamics codes (CFD) and decided to use FLUENT in detailed simulations. FLUENT offers several turbulence schemes including multiple variations of the k-ε models, as well as k-ω models, and Reynolds stress turbulence models. We used the standard, renormalized-group (RNG), and realizable k-ε turbulence closure scheme as it is the most commonly used model in street canyon flow and thermal stratification studies [5]. FLUENT incorporates the P-1 radiation model which affords detailed radiation transfer between the solar arrays, the ground and the ambient air; it also incorporates standard free convection and wind-forced convection models. Our choice of solver was the pressure-based algorithm SIMPLE which uses a relationship between velocity and pressure corrections to enforce mass conservation and obtain the pressure field. We conducted both three-dimensional (3-D) and 2-D simulations.

A 3-D model was built of four fields each covering an area of 93-meters by 73-meters (Fig. 10). Each field contains 23 linear arrays of 73-meter length and 1.8-meter width. Each array has 180 modules of 10.5% rated efficiency, placed facing south at a 25-degree angle from horizontal, with their bottom raised 0.5 m from the ground and their top reaching a height of 1.3 m . Each array was modeled as a single 73 m 1.8 m 1 cm rectangular. The arrays are spaced 4 meters apart and the roads between the fields are 8 m. Fig. 10 shows the simulated temperatures on the arrays at 14:00 pm on 7/1/2011, when the irradiance was 966 W/m^2. As shown, the highest average temperatures occur on the last array (array 46). Temperature on the front edge (array 1) is lower than in the center (array 23). Also, temperature on array 24 is lower than array 23, which is apparently caused by the cooling induced by the road space between two fields, and the magnitude of the temperature difference between arrays 24 and 46 is lower than that between arrays 1 and 23, as higher temperature differences from the ambient, result in more efficient cooling.

TABLE II
Modules Temperature

Arrays	1	23	24	46
Temperature ℃	46.1	56.4	53.1	57.8

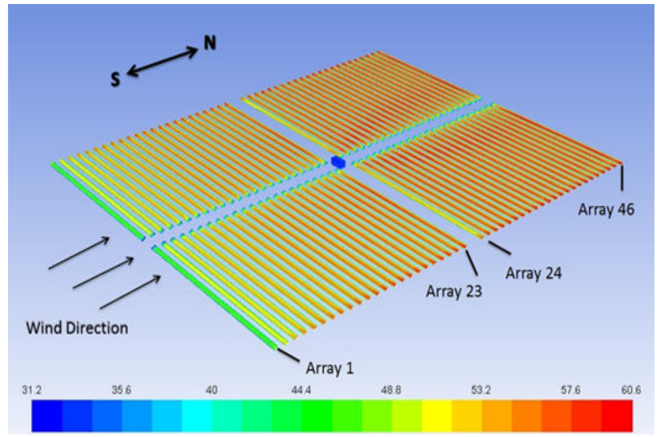
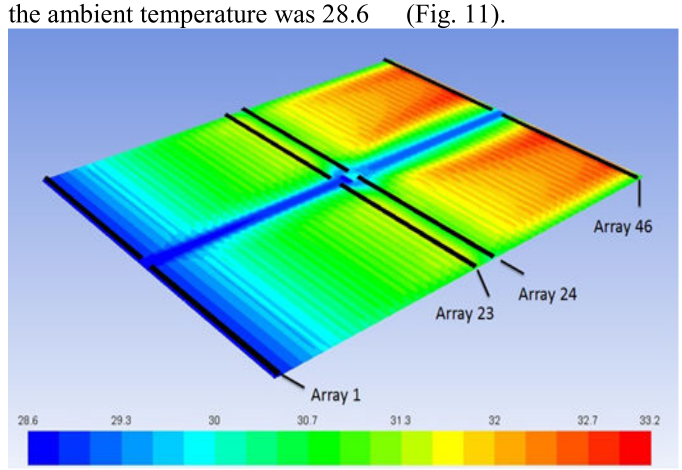
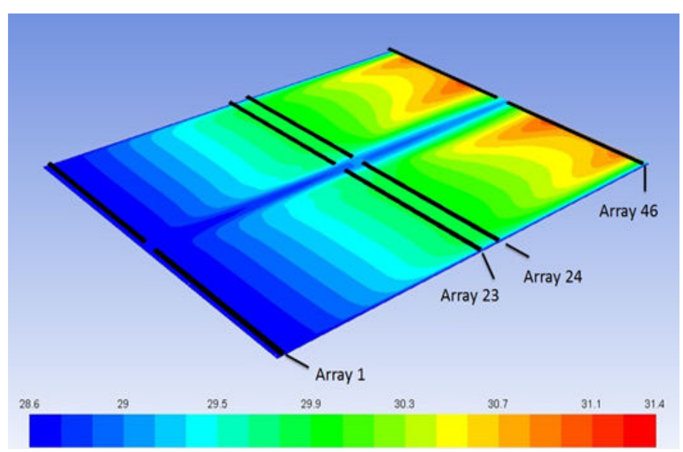


Fig. 10. Module temperatures from 3-D simulations of air flows and thermal exchange during a sunny day

Our simulations also showed that the air temperatures above the arrays at a height of 2.5 m ranged from 28.6 to 31.1 ; the ambient temperature was 28.6 (Fig. 11).



(a)



(b)

Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

TABLE III
AIR TEMPERATURE

Temperature	Ambient (℃)	Low (℃)	High (℃)	Average (℃)
2.5m height	28.6	28.6	31.1	30.1
1.5m height	28.6	28.6	33.2	30.8

These simulations show a profound cooling effect with increasing height from the ground. It is shown that the temperatures on the back surface of solar panels is up to 30°C warmer than the ambient temperature, but the air above the arrays is only up to 2.5°C higher than the ambient (i.e., 31.1℃). Also the road between the fields allows for cooling, which is more evident at the temperatures 1.5 m off the ground (Fig. 11a). The simulations show that heat build-up at the power station in the middle of the fields has a negligible effect on the temperature flow fields; it was estimated that a power station adds only about 0.4% to the heat generated by the corresponding modules.

The 3-D model showed that the temperature and air velocity fields within each field of the solar farm were symmetrical along the cross-wind axis; therefore a 2-D model of the downwind and the vertical dimensions was deemed to be sufficiently accurate. A 2-D model reduced the computational requirements and allowed for running simulations for several subsequent days using actual 30-min solar irradiance and wind input data. We tested the numerical results for three layers of different mesh sizes and determined that the following mesh sizes retain sufficient detail for an accurate representation of the field data: a) Top layer: 2m by 1m, b) Middle layer: 1.5m by 0.6m, c) Bottom layer: 1m by 0.4m. According to these mesh specifications, a simulation of 92 arrays (length of 388m, height 9m), required a total of 13600 cells. Figures 12-15 show comparisons of the modeled and measured module and air temperatures.

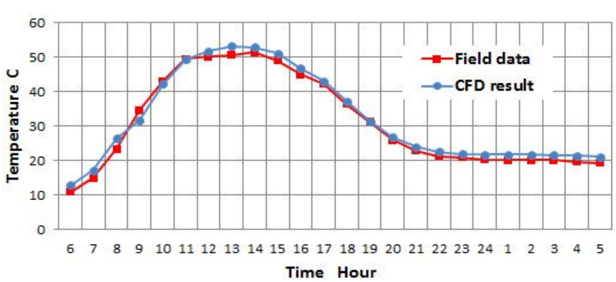


Fig. 12. Comparisons of field and modeled module temperatures; a sunny summer day (7/1/2011); 2-D simulations.

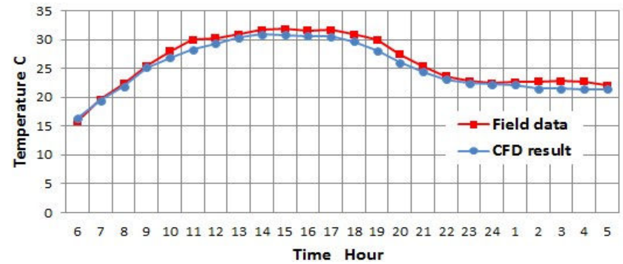


Fig. 13. Comparisons of field and modeled air temperatures at a height of 2.5 m; a sunny summer day (7/1/2011); 2-D simulations.

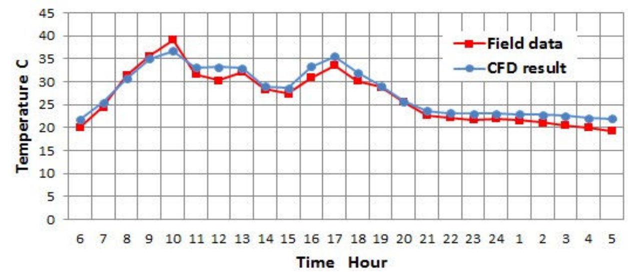


Fig. 14. Comparisons of field and modeled module temperatures; a cloudy summer day (7/11/2011); 2-D simulations.

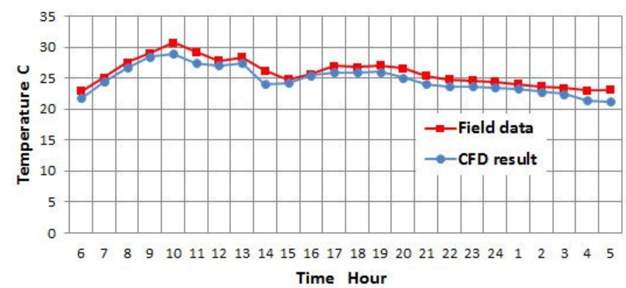
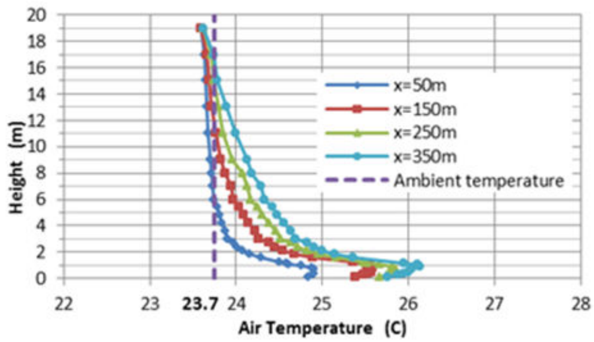
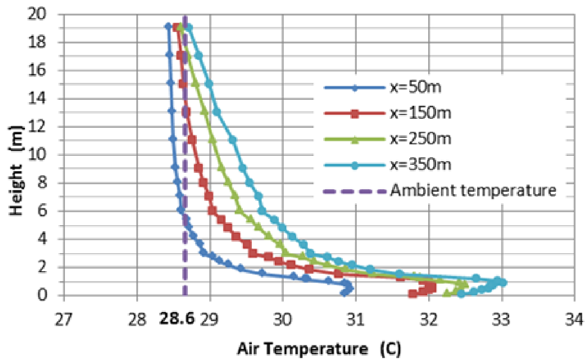


Fig. 15. Comparisons of field and modeled air temperatures at a height of 2.5 m; a cloudy summer day (7/11/2011); 2-D simulations.

Figures 16a and 16b show the air temperature as a function of height at different downwind distances in the morning and afternoon during a sunny summer day. At 9 am (irradiance 500 W/m2, wind speed 1.6 m/s, inlet ambient temperature 23.7℃), the heat from the solar array is dissipated at heights of 5-15m, whereas at 2 pm (irradiance 966 W/m^2, wind speed 2.8m/s, inlet ambient temperature 28.6℃ , the temperature of the panels has reached the daily peak, and the thermal energy takes up to 18 m to dissipate.



(a) 9:00 am



(b) 2:00 pm

Fig. 16 Air temperatures within the solar farm, as a function of height at different downwind distances. From 2-D simulations during a sunny summer day (7/1/2011) at 9 am and 2 pm.

IV. CONCLUSION

The field data and our simulations show that the annual average of air temperatures at 2.5 m of the ground in the center of simulated solar farm section is 1.9 higher than the ambient and that it declines to the ambient temperature at 5 to 18 m heights. The field data also show a clear decline of air temperatures as a function of distance from the perimeter of the solar farm, with the temperatures approaching the ambient temperature (within 0.3), at about 300 m away. Analysis of 18 months of detailed data showed that in most days, the solar array was completely cooled at night, and, thus, it is unlikely that a heat island effect could occur.

Our simulations also show that the access roads between solar fields allow for substantial cooling, and therefore, increase of the size of the solar farm may not affect the temperature of the surroundings. Simulations of large (e.g., 1 million m^2) solar fields are needed to test this hypothesis.

ACKNOWLEDGEMENT

We are grateful to First Solar for providing data for this study.

REFERENCES

[1] D. Turney and V. Fthenakis Environmental, "Impacts from the installation and operation of large-scale solar power slants," *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 3261-3270, 2011.

[2] F.G. Nemet. "Net radiative forcing from widespread deployment of photovoltaics," *Environ. Sci. Technol.*, vol. 43, pp. 2173-2178, 2009.

[3] M. Donovan, "Memorandum: impact of PV systems on local temperature, " *SunPower,* July 6, 2010. http://www.rurdev.usda.gov/SupportDocuments/EA_5_17_13_RUS_ PartA.pdf

[4] Y. Genchi, M. Ishisaki, Y. Ohashi, H. Takahashi, & A. Inaba, "Impacts of large-scale photovoltaic panel installation on the heat island effect in Tokyo, " *in Fifth Conference on the Urban Climate*, 2003.

[5] Theory Guide, *ANSYS Fluent HELP 13.*

Exhibit 3
Emergency Response Plan-
Construction

sPower

Emergency Response Plan - Construction

Spotsylvania Solar Energy Center – 500 MWac

Spotsylvania County, VA

November 27, 2018

Table of Contents

Appendices

Overall Site Plan and Site Access
Crisis Management Plan
Site Specific Safety Plan

1. General Information – Construction and Operation

The purpose of this plan is to discuss the procedures that will be implemented in the event of an emergency during the construction of the Spotsylvania Solar Energy Center.

1.1 Project Description

sPower is proposing to construct a 500 megawatt-AC photovoltaic (PV) single-axis tracker system. The final Project consists of three non-contiguous project sites (Site A, B, and C) that total approximately 6,350 acres, of which approximately 3,500 acres will be developed for the Project. The remaining 2,850 acres will be set aside as open space in Spotsylvania and Orange Counties, Virginia. It is located between Orange Plank Road on the north and W. Catharpin Road on the south. The approximate center of the site is located approximately 3.35 miles east of Mine Run, Virginia in Spotsylvania County, Virginia.

The Project's primary components include PV modules mounted on a single axis tracking system and solar inverters. The racking system foundations will utilize driven posts that would not require concrete. Other Project components include electrical cables, conduit, electrical cabinets, switchgears, step-up transformers, inverters, SCADA systems and metering equipment. The solar facility would be fenced and seeded in a low growth seed mix to reduce storm water runoff and erosion. **See Appendix 1:**

1.2 Project Team

Mortenson has the Engineering, Procurement, and Construction contract for the Spotsylvania Solar Energy Center. The Mortenson project team will consist of:

Table 1: Project Team Contact Info

Project Manager	TBD	Phone number (TBD)	email (TBD)
Superintendent	TBD	Phone number (TBD)	email (TBD)
Engineering and Permitting Manager	TBD	Phone number (TBD)	email (TBD)

1.3 Site Access

1.3.1 Site Address

Spotsylvania Solar Energy Center is in Spotsylvania County, VA. The address for the project is has not been established yet. The center of the project is located at latitude and longitude 38.24344° N and 77.77514°

1.3.2 Site Driveways

The Project is anticipated to have several site access locations, as the Project Site is not entirely accessible from a single site access location due to wetlands, streams, and topographical constraints. Primary access for Site A will be provided via Orange Plank Road (State Route 621) on the north and West Catharpin Road on the south; primary access for Site B will be provided via Post Oak Road (State Route 606) on the north; and primary access for Site C will be provided via West Catharpin Road on the north and Post Oak Road (State Route 606) and Chewing Place on the south. Site access locations will be improved and maintained to accommodate Spotsylvania County Fire, Rescue, and Emergency Services. Each access will be a 20-foot wide driveway with a 20-foot wide locked security gate. The security gate would be locked with a punch code key lock box, which would be dispatched to EMS services in the event of an emergency. This will be installed during construction and will remain for operation. Refer to section **4.4.1 Internal Site Access Roads and Driveways** for internal road and driveway specifications.

2 Site Specific Safety Plan

A Site Specific Safety Plan is included as **Appendix 3**

3 Crisis Management

Refer to the Spotsylvania Solar Energy Center Crisis Management Plan in **Appendix 2** for site specific information regarding who to contact in the event of an emergency.

3.1 Emergency Services Authority

The project's onsite superintendent will be responsible for overseeing emergency services compliance. His duties will include ensuring that the measures in this plan are complied with, any and all agencies are properly notified in the event notification is required, and that all required plans and reports are prepared and submitted in a timely manner.

The Mortenson project superintendent will be the emergency point of contact for the Spotsylvania Solar Energy Center. The superintendent's contact information is as follows:

TBD
Cell:
Office:
Email:

The Safety Manager will be responsible for project safety during all construction activities. Along with the superintendent, the Safety Manager will ensure that the measures in this plan are complied with, any and all agencies are properly notified in the event notification is required, and that all required plans and reports are prepared and submitted in a timely manner. The Safety Manager shall arrange and assign a backup in the event of their absence.

The Safety Manager point of contact is as follow:

TBD
Cell:
Office:
Email:

The point of contact over seeing electrical work is as follow:

TBD: The current position is being interviewed for and will be able to provide qualifications upon the County's request.

The point of contact over seeing mechanical work is as follow:

TBD: The current position is being interviewed for and will be able to provide qualifications upon the County's request.

The point of contact over seeing excavation work is as follow:

TBD: The current position is being interviewed for and will be able to provide qualifications upon the County's request.

Emergency Response Contact(s):

Medical Facility	**Address**	**Phone Number**	**Available Services**	**Distance from Project Site**
Spotsylvania Regional Medical Center	4600 Spotsylvania Parkway Fredericksburg, VA 22408	(540) 498-4000	Emergency Services	13 miles east of Site A

Fredericksburg Medical Center (Kaiser Permanente)	1201 Hospital Drive Fredericksburg, VA 22401	(540) 368-3700	Urgent Care Services	13 miles northeast of Site A
Mary Washington Hospital	1001 Sam Perry Boulevard, Fredericksburg, VA 22401	(540) 741-1100	Emergency Services	13.23 miles northeast of Site A

County Fire and Rescue Station	**Address**	**Phone Number**	**Distance from Project Site**
Fire Company/Rescue Station 7 (Wilderness)	10501 Orange Plank Road, Spotsylvania, VA 22553	Fire: (504) 507-7970/7971 Rescue: (540) 507-7952/7953	3.30 miles northeast of Site A
Fire Company/Rescue Station 9 (Belmont)	7100 Belmont Road, Mineral, VA 23117	Fire: (540) 507-7974/7975 Rescue: (540) 507-7956/7957	4.30 miles southwest of Site B
Fire Company/Rescue Station 2 (Brokenburg)	11700/11701 Volunteer Lane, Spotsylvania, VA 22553	(540) 507-7942/7943	5.75 miles southeast of Site C
Fire Company/Rescue Station 5 (Chancellor)	6204 Plank Road, Fredericksburg, VA 22407	Fire: (540) 507-7966/7967 Rescue: (540) 507-7948/7949	6.55 miles northeast of Site A

Local Police and Sheriff Station	**Address**	**Phone Number**	**Distance from Project Site**
Spotsylvania Sheriff	9119 Dean Ridings Ln, Spotsylvania Courthouse, VA 22553	(540) 507-7200	10 miles east of Site A
Orange County Sheriff's Office	11350 Porter Rd, Orange, VA 22960	(540) 672-1200	15.4 miles west of Site C
Fredericksburg Police Department	2200 Cowan Blvd, Fredericksburg, VA 22401	(540) 373-3122	18.9 miles northeast of Site A
Spotsylvania Animal Control	450 Tv Dr, Fredericksburg, VA 22408	(540) 582-7115	12 miles east of Site A

3.2 Communication and Training Procedures

All employees and subcontractors will receive safety training before they begin work onsite. This training will include pertinent information regarding hazardous material management and fire prevention. The project's superintendent will be responsible for ensuring that all personnel receive this training.

sPower will provide site specific training to County Fire that outlines construction and operation activity, a solar facility overview (location, ingress/egress, equipment, site operation), best practices in responding to emergencies at the facility, and thorough review of construction and operation emergency response plans. County Fire will receive maps of roads and facilities to access to the site with description locations. These maps will be incorporated into training materials to ensure that County Fire and EMS providers understand how and where to access emergency situations at the Project Site. sPower will host three separate training sessions with county FREM personnel spread out over the course of several months to allow for maximum participation. If, after the three sessions there are still FREM personnel who were unable to attend previous trainings, sPower will coordinate with County staff and FREM to schedule additional meetings

Communication will be available at all office trailers or a wireless amplifier will be installed for safety communication at job site trailers. Construction staff will be provided with adequate communication on site including radios to team leaders that are in constant communication with staff. Since cell phone service is limited at the project site, repeaters or cell phone boosters may be installed to enhance cell phone coverage across the site.

4 Fire Prevention

4.1 Purpose & Need for Fire Prevention Plan (FPP)

- Eliminate the potential risks and/or causes of fires
- Prevent loss of life and property by fire
- Educate employees to promote a safe environment
- Be prepared should a fire occur
- Outline a procedure to follow for the safety of the individuals on site at the time of the occurrence
- Identify risk factors and hazards
- Set up proper storage procedures, training, and identification of personnel responsible for maintaining and servicing the equipment and systems on site that are used to prevent and/or control a fire.

4.2 Responsibilities and Procedures

Safety is everyone's responsibility on site. All employees are to be trained and should know how to prevent and respond to a fire emergency. All employees must:
Complete an on-site training program identifying the fire risks for the project site
Know the protocol and follow emergency procedures should an event occur
Review and report potential fire hazards to the Superintendent

4.2.1 Understanding Conditions Associated with Photovoltaic Solar Arrays

Photovoltaic (PV) solar arrays present a unique challenge for fire fighters. Unlike a typical electrical or gas utility, a PV array does not have a single point of disconnect. Whereas there are disconnects that will de-energize select parts of the system, as long as the PV panels are illuminated, the individual strings of PV panels are energized and capable of producing up to 1,500 volts. This is not just limited to PV panels being illuminated by the sun; illumination by artificial light sources, such as fire department lights, or the light for the fire itself are capable of producing electrical power sufficient to cause a lock-on hazard (Source: *UL Firefighter Safety and Photovoltaic Installations Research Project, November 29, 2011*). Below is a summary of the hazards associated with firefighting activities in photovoltaic solar arrays:

- Shock hazard due to the presence of water and PV power during suppression activities
- Outdoor rated electrical enclosures may not resist water intrusion from the high-pressure stream of a fire hose.
- PV panels damaged in the fire may not resist water intrusion.
- Damaged conductors may not resist water intrusion
- Shock hazard due to direct contact with energized components
- No means of complete electrical disconnect.

Due to the dangers presented above, it is not typical to practice fire suppression by means of water inundation within solar PV arrays.

4.2.2 Small Stage Fires

Small stage fires are small fires that are in the beginning stage and can be controlled with a fire extinguisher. An example would be a small trash can fire. In the event of a small stage fire at the project:

1. The person discovering the fire should immediately dispatch someone to activate the Incident Command Team.
2. All non-essential personnel should be removed from the hazard area.
3. All on-site vehicles are required to carry fire extinguishers. Fire extinguishment with a fire extinguisher or other means should be attempted if the person has been trained in the use of fire extinguishers and can do so without placing themselves in danger.
4. The Safety Manager or his designee will respond to the scene and determine if external resources or an evacuation are necessary. In the event of an evacuation, they will recruit/dispatch employees to assist with the evacuation and, have the Superintendent issue the following statement over the radio: “Attention, there is a fire emergency at (location name). Please evacuate (the affected area) and report to (designated meeting area).
5. Fire department shall be notified of incident including the nearest access point and location of fire. A site safety employee shall meet EMS services and escort the EMS response team to the incident. In the event EMS services do not respond at a single time, additional personnel shall be appointed to meet remaining EMS services at the access gate and escort them to the fire location.
6. Designated meeting areas shall be established at all primary site entrances. EMS services shall be notified of designated meeting area during small stage fires.
7. At this point, all employees in the affected area will stop work immediately, take steps to safely shut down equipment, exit the evacuation area, and report to the designated meeting area.
8. The Safety Manager will then take steps to ensure that no employee re-enters the evacuated area until the Fire Department arrives and assumes command.
9. The Safety Manager will issue an “All Clear” only when the Fire Department informs them that it is safe to do so.

4.2.3 Large Stage Fires

In the event of a large stage fire at the project:
The person discovering the fire should immediately contact the Safety Manager or Superintendent.

1. Call 911 to report the fire.
2. Fire department shall be notified of incident including the nearest access point and location of fire. A site safety employee shall meet EMS services and escort the EMS response team to the

incident. In the event EMS services do not respond at a single time, additional personnel shall be appointed to meet remaining EMS services at the access gate and escort them to the fire location.

3. All personnel should be removed from the immediate danger area in anticipation of an evacuation.
4. Designated meeting areas shall be established at all primary site entrances. EMS services shall be notified of designated meeting area during large stage fires. The Safety Manager will respond to the scene and ensure that the fire department has been dispatched. Spotsylvania County Fire, Rescue and Emergency Management will be responding to 911 calls during construction and after construction has completed. They will then determine evacuation needs, recruit/dispatch employees to assist with the evacuation and, have the Superintendent issue the following statement over the radio: "Attention, there is a fire emergency at (location name). Please evacuate (the affected area) and report to (designated meeting area).
5. At this point, all employees in the affected area will stop work immediately, take steps to safely shut down equipment, exit the evacuation area, and report to the designated meeting area.
6. In this scenario, fire extinguishers are to be used for escape purposes only.
7. The Safety Manager will take the necessary steps to ensure that no employee re-enters the evacuated area until the Fire Department arrives and assumes command.
8. No employee is required or permitted to place themselves in harm's way in order to facilitate extinguishment, evacuation, or rescue. All rescue operations will be performed by trained professionals upon their arrival.
9. The Safety Manager will issue an "All Clear" only when the Fire Department informs them that it is safe to do so.

4.3 Vegetation Fire and Procedures

The site will be largely free of combustible vegetation with only a ground cover of maintained vegetation adjacent and beneath the solar tracker (Figure 1). Flying embers from off-site fire may inundate the Project area during fire events. The modified fuel areas and construction type and materials for all project features will resist ignition from ember showers. Ignition of the ground cover could result in a fast moving, but lower intensity fire that burn in a patchy manner on the site beneath the modules. The vegetation on the Gen-tie line right-of-way will be cleared around poles and access roads, where not prohibited by environmental constraints. This type of fire would be relatively short-duration as vegetative fuels are consumed rapidly. There would not be a sustained source of heat and or flame as there would be with surrounding wild fires.

Figure 1: Typical Ground Cover Under Solar Arrays

In the event of a vegetation fire under or near the modules or inverters:

- **DO NOT** attempt to extinguish the flames with water or other chemicals as an electric shock or arc could occur.
- If possible, safely attempt to shut down power at the inverter using the DC disconnect
- Let the fire burn vegetation and self-extinguish
- If flames continue away from modules or inverters, attempt to extinguish flames.

4.4 Fire Department Access

4.4.1 Internal Site Access Roads and Driveways

The internal site access roads will consist of compacted gravel roads. These access roads will be located to provide access to each of the sites Photovoltaic Module Inverter Station (a.k.a. power conversion stations). This is the location where the solar inverters and step up transformers will be located. Access roads located throughout the arrays are a minimum 12 feet wide and provide 50-feet turning radius and standard hammer-head turnarounds at inverter locations. These internal access roads are provided primarily for use by operations and maintenance personnel vehicles. All internal roads and crossings will be permanent and designed (at a minimum) to FAST Act standards, for EV2 and EV3 class vehicles, with a rating as defined as H-20 per the VDOT IIM-S&B-86.1 guidance document.

4.4.2 Access Aisles

From the internal access roads, access to all areas within the solar arrays is provided by access aisles. Access aisles are the clear spaces located between the individual rows of solar panels. Access aisles consist of unimproved native material and are not suitable for all emergency services vehicles. However, access aisles do provide emergency responders with access routes to all areas of the site via walking from a nearby access road or by the use of 4x4 vehicles.

4.5 Controlling Hazards & Prevention Practices

For a FPP to be effective, fire hazards need to be identified and controlled. Employees need to be educated on fire hazards associated with a PV power plant and what procedures to follow to prevent and control fire hazards. Employees need to know how to respond to the fires those hazards might cause.

4.6 Welding & Open Flame/Hot Work

Cutting, welding, and open flame work are naturally hazardous. Welding processes may use oxy-acetylene gas, electrical current, electron beams, and heat from fuel gas. It is critical that the highest level of attention be given to these activities to prevent fires at a PV power plant.

- Cutting and welding are to be done by authorized personnel.
- Torches, regulators, pressure-reducing valves and manifold are to be UL listed or FM approved.
- Welders are to wear eye protection and protective clothing as appropriate.
- Oxygen-fuel gas systems are to be equipped with listed and or approved backflow valves and pressure-relief devices.
- Prior to open flame or hot work activity, a Fire Watch Person shall be established.

Establish a Fire Watch Person when prior to welding, open flame or hot work activity.
Fire extinguishers shall be present at all times during welding and open flame/hot work.

4.7 Burning

sPower will comply with the State of Virginia Regulation for Open Burning (9 VAC 5 -130) and the Spotsylvania County Code of Ordinances Chapter 9 - Article IV - Open Air Burning. sPower and its contractor shall mulch stumps, tree limbs and other woody debris where possible for use as erosion control BMPs. In the event material cannot be mulched or used on the Project Site, special incineration devices (i.e. open pit incinerators) that provide good and clean combustion performance shall be permitted, but at no time closer than 2,000 feet from any residence.

An AirBurner 2018 Model T-300 Trench Burner, or similar technology, will be deployed in designated areas during initial grading of the Project site. The following protocols will be implemented when trench burning occurs:

- A permit shall be acquired from Spotsylvania County.
- All combustible materials shall be removed within 35 feet of trench burning.
- A water truck shall be on standby.
- Trench burning shall not occur within 2,000 feet of any residence.
- Trench burners shall be equipped with fire extinguishers.
- Check wind forecasts for the day and do not burn on high wind days (sustained winds more than 25 mph) or when prohibited by Spotsylvania County Fire Department.
- Burning shall take into consideration sensitive receptors and prevailing wind direction at lower speeds (<25 mph).Burning shall cease 2 hours prior to end of work day.
- Employees that operate trench burners will be issued a hot work permit.
- Each trench burning shall be staffed by a minimum of 2 employees.
- A Fire Watch Person will be designated to monitor all trench burning activities.
- The Fire Watch Person shall remain within the immediate area of the trench burning at all times and shall not be assigned any other duties.
- The Fire Watch Person shall complete a "Hot Work Checklist" each day trench burning occurs.
- If the burn area is still producing smoke, it is technically stull burning and must be attended.

Trenches will be dug to depths indicated by the trench burner's technological specs or Fire Marshall guidance, in order to limit exposure to wind and gusts. A blowing machine is utilized to pump air into the trench, increasing the fire temperature, and thus burning the material quickly and efficiently. This eliminates excess smoke and embers.

4.8 Class A Combustibles

These combustibles consist of common materials (wood, paper, cloth, rubber, and plastic) that can act as fuel and are found on most work sites.
To handle Class A combustibles safely to prevent fires:

- Dispose of waste daily (i.e. cardboard, wood pallets, packing materials etc.).
- No burning of these construction materials shall occur.
- Use trash receptacles with covers.
- Keep work areas clean and free of combustible materials.
- Store materials in the proper storage and recycling containers.
- Do a periodic check of the job site to make sure combustibles are being handled correctly.
- Water, multi-purpose dry chemical (ABC) and halon are approved fire extinguishing agents for Class-A Combustibles.

4.9 Class B Combustibles

These combustibles include flammable and combustible liquids (oil, grease, tar, oil-based paints and lacquers) flammable gases, and flammable aerosols.
To handle Class B combustibles safely to prevent fires:

- Use only approved pumps (with suction from the top) to dispense liquids from tanks, drums, barrels, or similar containers (or use approved self-closing valves or faucets).

- Do not dispense Class B flammable liquids into a container unless the nozzle and container are electrically interconnected by contact or bonding wire. Either the tank or container must be grounded.
- Store, handle, and use Class B combustibles only in approved locations where vapors are prevented from reaching ignition sources such as heating or electric equipment, open flames, or mechanical or electric sparks.
- Do not use a flammable liquid as a cleaning agent inside a building (the only exception is in a closed machine approved for cleaning with flammable liquids).
- Do not use, handle, or store Class B combustibles near exits, stairs, or any other areas normally used as exits.
- Do not weld, cut, grind, or use unsafe electrical appliances or equipment near Class B combustibles.
- Do not generate heat, allow an open flame, or smoke near Class B combustibles.

Know the location of and how to use the nearest portable fire extinguisher rated for Class B fire.
Water should not be used to extinguish Class B fires caused by flammable liquids, as it can cause the burning liquid to spread, making the fire worse. To extinguish a fire caused by flammable liquids, exclude the air around the burning liquid. The following fire extinguishing agents are approved for Class B combustibles: carbon dioxide, multi-purpose dry chemical (ABC), halon 1301 and halon 1211. (Halon is no longer being manufactured due to its designation as an ozone-depleting substance).

4.10 Class C Combustibles

Class C fires are fires that involve energized electrical equipment. In the event of a Class C fire, <u>ALWAYS</u> de-energize the circuit supplying the fire, and then use a non-conductive extinguishing agent such as carbon dioxide or Halon 1211. A multi-purpose dry chemical (ABC) extinguisher can also be used on Class C fires.
Do not use water, foam or other conducive agents when fighting electrical fires. Once the electricity is shut down to the equipment involved, the fire generally becomes a standard combustible fire.

4.11 Electrical Fire Hazards

Electrical equipment is a major cause of workplace fires and may result from loose ground connections, wiring with bad insulation, or overloaded fuses, circuits, motors or outlets.
To prevent electrical fires, the following measures will be taken:

- Use only appropriately rated fuses per manufacture’s specifications.
- Check all electrical equipment to ensure it is properly grounded and insulated.
- Ensure adequate spacing while performing maintenance.
- Check wiring to ensure no damage to cables or connections.

4.12 Employee Training & Education

Job site fire rules are to be posted on the project the bulletin board along with the OSHA compliance postings, first aid, and site specific project information. The bulletin board is to be located at the contractor’s field office and accessible to all employees.

Personnel shall be trained in the practices of the fire safety plan relevant to their duties. Construction and maintenance personnel shall be trained and equipped to extinguish small fires to prevent them from growing into more serious threats. Confirm all employees understand the function and elements of the fire safety plan, including types of potential emergencies, reporting procedures, evacuation plans, and shutdown procedures. Review any special hazards that might occur at the Spotsylvania Solar Energy Center, such as flammable materials, fuel storage, toxic chemicals, and water reactive substances.

Fire safety training will occur during the site safety training. Every employee must take this training before starting work. Training to include:

- Employee roles and responsibilities.
- Recognition of potential fire hazards.
- Alarm system and evacuation routes.
- Location and operation of manually operated equipment (fire extinguishers).
- Emergency response procedures.
- Emergency shutdown procedures.
- Information regarding specific materials to which employees may be exposed.
- Review OSHA requirements contained in 29 CFR 19010.38, Emergency Action Plans.
- Review OSHA requirements contained in 29 CFR 1910.39, Fire Prevention Plans.
- The location of the company FPP and how it can be accessed.
- Good fire-prevention housekeeping practices and equipment maintenance.

The Mortenson site safety person, as well as the Superintendents and Foreman, are responsible for fire safety training. Written documentation of the training received by each employee must be maintained.

4.13 Use of Portable Fire Extinguishers

A minimum of one portable fire extinguisher should be provided within 200 feet of anywhere in the work area during construction.

- Fire extinguishers should be inspected monthly.
- Fire extinguishers should not be obstructed and should be in conspicuous locations.

4.14 Site Maintenance & Housekeeping

- Combustible material should not be stored in mechanical rooms, electrical equipment rooms or the SCADA buildings.
- Outside dumpsters should be kept at least 5 feet away from combustible materials and the lid should be kept closed.
- Storage is not allowed in electrical equipment rooms, or near electrical panels.
- Electrical panel openings must be covered.
- Power strips must be plugged directly into an outlet and NOT daisy-chained and should be for temporary use only.
- Extension cords and flexible cords should not be substituted for permanent.

4.15 Equipment Fire Safety

- All internal combustion engines, both stationary and mobile, shall be equipped with spark arresters. Spark arresters shall be in good working order.
- Light trucks and cars with factory-installed (type) mufflers shall be used only on roads where the roadway is cleared of vegetation. These vehicle types shall maintain their factory-installed (type) mufflers in good condition.

- Equipment parking areas and small stationary engine sites shall be cleared of all extraneous flammable materials.
- The project proponent shall make an effort to restrict the use of chainsaws, chippers, vegetation masticators, grinders, drill rigs, tractors, and torches to periods outside of the official fire season. When the above tools are used, water tanks equipped with hoses, fire rakes, and axes shall be easily accessible to personnel.
- All team supervisors and health and safety officials will have AED and first aid kits in vehicles.

4.16 Emergency Response

Project personnel will meet with local emergency response groups to review the Fire Safety Plan, discuss the type of work taking place, duration of project schedule and emergency procedures.
The following course of action should be taken if an emergency develops:

- Evacuation procedures and assembly are contained in the Evacuation plan, which will be posted in all office trailers. Maintain site security and control.
- Notify proper emergency services for assistance. Dial 911 or direct-dial emergency contact numbers if possible. Emergency numbers shall be posted at each office trailer.
- Notify Site Safety Manager and all affected personnel at the site through use of site radio or other communication devices.
- Once emergency personnel have been notified, an employee will then be designated to meet the emergency personnel at the point of ingress and then guide them to incident location. If emergency personnel come at different times, a secondary person will meet the subsequent crews at the ingress point.
- Only after emergency is declared over by the Site Safety Manager can all other radio communication resume.
- Prepare a summary of the incident as soon as possible and no later than 24 hours after the incident.

This FPP is in addition to Mortenson's standard Safety protocol and is to be a part of daily tool box topics, reviewed regularly, and included in general safety meetings and review with Safety Manager and on site personal.

5 Severe Weather

5.1. Severe Thunderstorm and Tornado Warnings

A severe thunderstorm or tornado warning is an urgent announcement that a severe thunderstorm or Tornado has been reported or is imminent in the area and will warn individuals to take cover. Local National Weather Service office issue severe thunderstorm or tornado warnings.

Notification systems for adverse weather, which may include NOAA radio, AM/FM radio, lightning detectors, wind speed indicators, will be maintained at the project Operations and Maintenance (O&M) building and/or MET stations throughout the project site.

In addition, weather will be monitored utilizing http://www.nws.noaa.gov/

5.1.1. Thunderstorms

Upon hearing the sound of thunder, personnel are close enough to a storm to be struck by lightning. Employees will be instructed to go to a designated safe shelter immediately.
In addition:

- Crane activities will be shut down.
- Workers will be removed from elevated areas.
- If no shelter is nearby, workers will be instructed to get in a vehicle and keep the windows up.
- If indoors, unnecessary appliances will be unplugged and phone use will be strictly for emergencies.
- If personnel are caught outside and no shelter is available, they will be instructed as follows:
- Find a low spot away from trees, fences, and poles.
- Squat low to the ground on the balls of your feet, place your hands on your knees with your head between them, make yourself the smallest target possible and minimize your contact with the ground.

5.1.2 Tornados

Upon the issuance of a tornado warning, employees will evacuate the job site and report to the pre-designated shelter area, to be determined prior to employee arrival. In the event employees are outside and unable to evacuate to the shelter, the following procedure will be followed:

- Lie flat in a nearby ditch or depression, covering the head with the hands. Be aware of the potential for flooding.
- Employees are safest in a low, flat location and will be instructed to not get under an overpass or bridge.
- Employees will be instructed to never try to outrun a tornado in congested areas in a vehicle. It is safest to leave the vehicle for safe shelter.
- Employees will be instructed to watch out for flying debris.

5.2 Floods

It's important to be careful when driving during flood conditions. Nearly half of flood fatalities are vehicle-related. Six inches of standing water is enough to stall some cars, a foot of water can float a vehicle, and two feet of moving water is enough to sweep a car away. If the water level is rising around your vehicle, you should abandon the vehicle. Be wary of unknown road conditions. Do not try to cross flooded roadways if you do not know the depth of the water.

Determine whether your home or work place is in a predetermined flood plain. Stay informed about and know flood terminology:

- Flood Watch—Flooding is possible. Stay tuned to radio or TV for more information.
- Flash Flood Watch—Flash flooding is possible. Stay tuned to radio or TV for more information. Be prepared to move to higher ground.
- Flood Warning—Flooding is currently occurring or will occur soon. Listen for further instructions. If told to evacuate, do so immediately.
- Flash Flood Warning—Flash flooding is currently occurring or will occur soon. Seek higher ground on foot immediately.

5.2.1 Chemical and biological hazards

Liquefied Petroleum Gases (LPG) and underground storage tanks, along with other chemical containers, may break away and float downstream, causing hazards from their released contents. Floodwaters may also contain biohazards due to direct contamination by untreated raw sewage, dead animals, rotting food, etc. Avoiding contact, good personal hygiene practices, medical surveillance, and discarding all food that comes in contact with flood waters are all important controls.

5.2.2 Fire

Floods can damage fire protection systems, delay response times of emergency responders and disrupt water distribution systems. All of these factors lead to increased dangers from fire and decreasing firefighter capabilities.

5.2.3 Drowning

Anytime workers are exposed to moving water, their chances for accidental drowning increases. Even good swimmers are easily overcome by swift-moving water.

5.2.4 Hypothermia

Hypothermia is a condition brought on when the body temperature drops to less than 95°F. Standing or working in water that is cooler than 75°F will remove body heat more rapidly than it can be replaced, resulting in hypothermia. Symptoms of hypothermia include uncontrollable shivering, slow speech, memory lapses, frequent stumbling, drowsiness, and exhaustion.

6. Hazardous Materials

6.1 Hazardous Materials on Site

Mortenson does not anticipate utilizing many hazardous materials for the construction of the Spotsylvania Solar Energy Center. One (1) 1000-gallon temporary diesel fuel tank and Two (2) 250-gallon temporary gasoline tanks are the only anticipated hazardous materials to be stored on site during construction.

6.1.1 Container Management:

- All hazardous substance containers must be in good condition and compatible with the materials stored within.
- All hazardous substance containers must be accessible and spacing between containers must provide sufficient access to perform periodic inspections and respond to releases.
- Fuel stored on site shall have secondary containment and must be located greater than 250 feet from wetlands and RPA zones.
- Jersey barriers will be placed around fuel tanks where applicable for additional security.
- All fueling shall occur greater than 250 feet from wetlands and RPA zones.
- Empty hazardous substance containers (drums) must have all markers and labels removed and the container marked with the word “empty”.
- Any spills on the exterior of the container must be cleaned immediately.

- Flammable materials stored or dispensed from drums or totes must be grounded to prevent static spark.
- Do not overfill waste drums. 4" of headspace must remain to allow for expansion.

6.1.2 Good Housekeeping:

- All hazardous substances must be stored inside buildings or under cover.
- Store hazardous substances not used daily in cabinets, or in designated areas.
- All chemicals that are transferred from larger to smaller containers must be transferred by use of a funnel or spigot.
- All hazardous substance containers should be closed while not in use.
- Use drip pans or other collection devices to contain drips or leaks from dispensing containers or equipment.
- Implement preventative maintenance activities to reduce the potential for release from equipment.
- Immediately clean up and properly manage all small spills or leaks.
- Periodically inspect equipment and hazardous substance storage areas to ensure leaks or spills are not occurring.
- Use signage to identify hazardous substance storage or waste collection areas;
- Keep all work areas and hazardous substance storage areas clean and in good general condition.
- Verify weekly that spill control clean-up materials are located near material storage, unloading, and use areas.
- Update spill prevention and control plans and stock appropriate clean-up materials whenever changes occur in the types of chemicals used or stored onsite.

6.1.3 Secondary Containment:

Store all bulk chemicals (≥55 gallons) within appropriate secondary containment, or any sized chemical if there is a potential for release to the environment.
Secondary containment should be checked periodically, and any spills identified in secondary containment must be immediately cleaned up and removed.

6.1.4 Marking/Labeling:

Ensure all hazardous substances, including chemical wastes, are properly marked and labeled in accordance with all federal, state and local regulations.
Ensure that hazardous substances transferred to small containers are marked with the chemicals name (example- "Isopropyl Alcohol") and hazard (example- "Flammable").

6.2 Spill Response Plan

All spills shall be immediately addressed and reported to the appropriate agencies. In the unlikely event of a hazardous materials spill into an Resource Protection Area (RPA), wetland, or stream, Spotsylvania County EMS and the Zoning Department shall be notified immediately.

6.2.1 Minor Spills

Minor spills typically involve small quantities of oil, gasoline, paint, etc., which can be controlled by the first responder at the discovery of the spill. Below are the steps that should be taken to control minor spills:

- Use absorbent materials on small spills rather than hosing down or burying the spill.
- Remove the absorbent materials promptly and dispose of properly.
- The practice commonly followed for a minor spill is:
- Contain the spread of the spill.
- Recover spilled materials.
- Clean the contaminated area and/or properly dispose of contaminated materials.

6.2.2 Semi-Significant Spills

Semi-significant spills still can be controlled by the first responder along with the aid of other personnel such as laborers and the foreman, etc. This response may require the cessation of all other activities. Below are the steps that should be taken to control semi-significant spills:

- Clean up spills immediately.
- Notify the project foreman immediately. The foreman shall notify the Engineer.
- Contain spread of the spill.
- If the spill occurs on paved or impermeable surfaces, clean up using "dry" methods (absorbent materials, cat litter and/or rags). Contain the spill by encircling with absorbent materials and do not let the spill spread widely.
- If the spill occurs in dirt areas, immediately contain the spill by constructing an earthen dike. Dig up and properly dispose of contaminated soil.
- If the spill occurs during rain, cover spill with tarps or other material to prevent contaminating runoff.

6.2.3 Significant/Hazardous Spills

For significant or hazardous spills that cannot be controlled by personnel in the immediate vicinity, the following steps shall be taken:

- Notify the Engineer immediately and follow up with a written report.
- Notify the local emergency response by dialing 911. In addition to 911, the contractor will notify the proper county officials. It is the contractor's responsibility to have all emergency phone numbers at the construction site.
- For spills of federal reportable quantities, in conformance with the requirements in 40 CFR parts 110,119, and 302, the contractor shall notify the National Response Center at (800) 424-8802.
- Notification shall first be made by telephone and followed up with a written report.
- The services of a spills contractor or a Haz-Mat team shall be obtained immediately. Construction personnel shall not attempt to clean up the spill until the appropriate and qualified staff has arrived at the job site.

Other agencies which may need to be consulted include, but are not limited to, the Fire Department, the Public Works Department, the Coast Guard, the Highway Patrol, the City/County Police Department, Department of Toxic Substances, OSHA, RWQCB, etc.

6.3 Education

Education regarding hazardous materials shall be conducted as part of the Mortenson site safety training for both new employees and as a refresher for existing employees transferring onto this project. The training shall:

- Educate employees and subcontractors on what a "significant spill" is for each material they use, and what is the appropriate response for "significant" and "insignificant" spills.
- Educate employees and subcontractors on potential dangers to humans and the environment from spills and leaks.
- Hold regular meetings to discuss and reinforce appropriate disposal procedures (incorporate into regular safety meetings).
- Establish a continuing education program to indoctrinate new employees.

The Contractor's Water Pollution Control Manager (WPCM) shall oversee and enforce proper spill prevention and control measures. The Mortenson superintendent will be the WPCM for this project.

6.4 Maintenance and Inspection

Hazardous material maintenance and inspection shall consist of the following:
Verify weekly that spill control clean-up materials are located near material storage, unloading, and use areas.

Update spill prevention and control plans and stock appropriate clean-up materials whenever changes occur in the types of chemicals used or stored onsite.

Exhibit 4
Emergency Response Plan-
Operations

Emergency Response Plan - Operations
Spotsylvania Solar Energy Center
November 27, 2018

1.0 INTRODUCTION

The purpose of the Emergency Response Plan is to establish responsibility and guidelines for taking action in the event of an emergency occurring at the Spotsylvania Solar Energy Center (Project) Site during operation of the Project. The Emergency Response Plan emphasizes sPower's dedication to providing a safe and healthy work environment. sPower employees and Operations and Maintenance (O&M) staff working at the Project Site shall familiarize themselves with the content of this Emergency Response Plan, so they can understand and comply with instructions and procedures outlined herein.

1.1 General Responsibilities

sPower is accountable for the safety of employees working under their supervision and are required to enforce the instructions and procedures outlined herein. All on-site personnel must take an active part in protecting themselves, fellow workers, and the general public. They are further required to participate in safety meetings and notify supervisors of any unsafe conditions that may exist at the Project Site. The following is a list of the general responsibilities of on-site personnel.

<u>Operations and Safety Managers</u>

More than any other employee, Superintendents and Supervisors carry the greatest burden of implementing, maintaining, and enforcing the Emergency Response Plan at the Project Site. Their responsibilities include:

- Ensure job specific emergency and evacuation procedures are provided at the Project Site.
- Evaluate workers qualifications and abilities.
- Ensure that workers have proper clothing and personal protective equipment.
- Provide all personnel and sPower vehicles with equipment necessary to respond to first aid, health and safety issues, fire or other emergency needs including equipping sPower vehicles with fire extinguishers, first aid kits and AED equipment.
- Provide first aid and ensure employees have access to medical treatment.
- Conduct safety meetings that emphasize the importance of safety and address specific jobsite safety issues.
- Plan and anticipate potential hazards of upcoming work.
- Conduct workplace safety inspections and be alert for possible accident producing conditions.
- Follow-up to ensure compliance with safety recommendations made by sPower, Spotsylvania County, the County Fire Marshal, the Police Department, and regulatory agencies.
- Provide training to County first responders that provides a solar facility functional overview (location, ingress/egress, equipment, site operation), evaluates operation activities and best practices in responding to emergencies at the facility, and reviews operation emergency response plans.

Worker Responsibilities

Each and every worker is responsible for the safety of themselves and their fellow workers. In addition to observing safe practices and exercising common sense, worker responsibilities include:

- Adhere to all instructions and procedures contained herein and established by Supervisors.
- Be constantly vigilant for unsafe activities or conditions around work activities and make the needed corrections.
- Set a good example for fellow workers.
- Consistently deliver work of high quality.
- Cooperate with Supervisors in preventing accidents.
- Make safety suggestions and/or report safety concerns to Supervisors.

Jobsite Visitors

On occasion, sPower will receive requests from County staff, emergency services, project sponsors, public organizations, or others to visit the Project Site. Jobsite visitors shall undergo site safety orientation prior to entering the Project Site.

1.2 General Guidelines

On-site personnel will have to take actions as their judgment dictates based upon the conditions that arise for each emergency. These guidelines are intended to assist them in making timely decisions and taking appropriate actions. On-site personnel shall call for assistance, based on the significance of the emergency. All work-related injuries/illnesses MUST be reported IMMEDIATELY to sPower.

- If the emergency requires external emergency responders to arrive on the Project Site, the initial responder must coordinate the response. For emergencies of a significant nature, such as fire or ambulance for major medical emergency, the initial responder shall call 911, and then use the Calling Tree.
- Subcontractor Management are responsible for getting injured parties to the hospital and emergency treatment at the nearest heath care facilities in the most efficient manner possible based on perceived injuries, using ambulance, paramedic units, or Air Evacuation as needed.
- For all first aid medical incidents, use the Calling Tree to notify Site Response Personnel to help provide support. For non-emergency situations like a minor injury, the initial responder shall use the Calling Tree.
- Subcontractor Safety Personnel shall accompany the injured party and use the local occupational medical clinic or hospital nearest the Project Site.
- Subcontractors must establish their own First Aid stations. They shall be made available to their workforce and provided in each trailer and in all trucks on the Project Site.

Alarm Descriptions

Emergency	Description
Medical	1 air horn blast with simultaneous cell phone notification
Fire	2 air horn blasts with simultaneous cell phone notification
Evacuation	3 air horn blasts with simultaneous cell phone notification
Seek Shelter	4 air horn blasts with simultaneous cell phone notification

2.0 MEDICAL EMERGENCY

2.1 Serious Injury

The following procedures apply for serious medical injuries such as loss of consciousness, heart attack, bone fractures, neck trauma, or severe burns.

1. One (1) air horn blast with simultaneous cell phone notification.
2. Broadcast "May-Day, May-Day" on radio.
3. Notify Operations and/or Safety Managers.
4. If life threatening, call **9-1-1.**
5. Provide name, exact location, number of injured persons, and brief description of incident
6. On-site personnel to meet EMS responders at site entrance and direct them to location of incident.
7. Do not leave or move the injured unless directed to by Safety Managers or EMS responders.
8. Administer first aid if necessary.
9. Document incident and keep on file.

2.2 Minor Injury

The following procedures apply for minor medical injuries.

1. One (1) air horn blast with simultaneous cell phone notification.
2. Initiate first aid if necessary.
3. Notify Operations and/or Safety Managers.
4. Call **9-1-1** if necessary.
5. Arrange for visit to medical facility as needed.

2.3 Attending an Incident

When attending an incident, the following procedures apply:

1. Clear a path to the injured person for Operations and/or Safety Managers and assign personnel to assist with signaling EMS responders to the location of the incident.
2. Identify location of Project Site entrance nearest to the incident and notify EMS responders.
3. Operations and/or Safety Managers shall meet EMS responders at site entrance.
4. Direct and accompany EMS responders to location of incident.
5. Follow all directions of EMS responders

6. Contact management staff of sPower and/or subcontractors.
7. Document incident and keep on file.

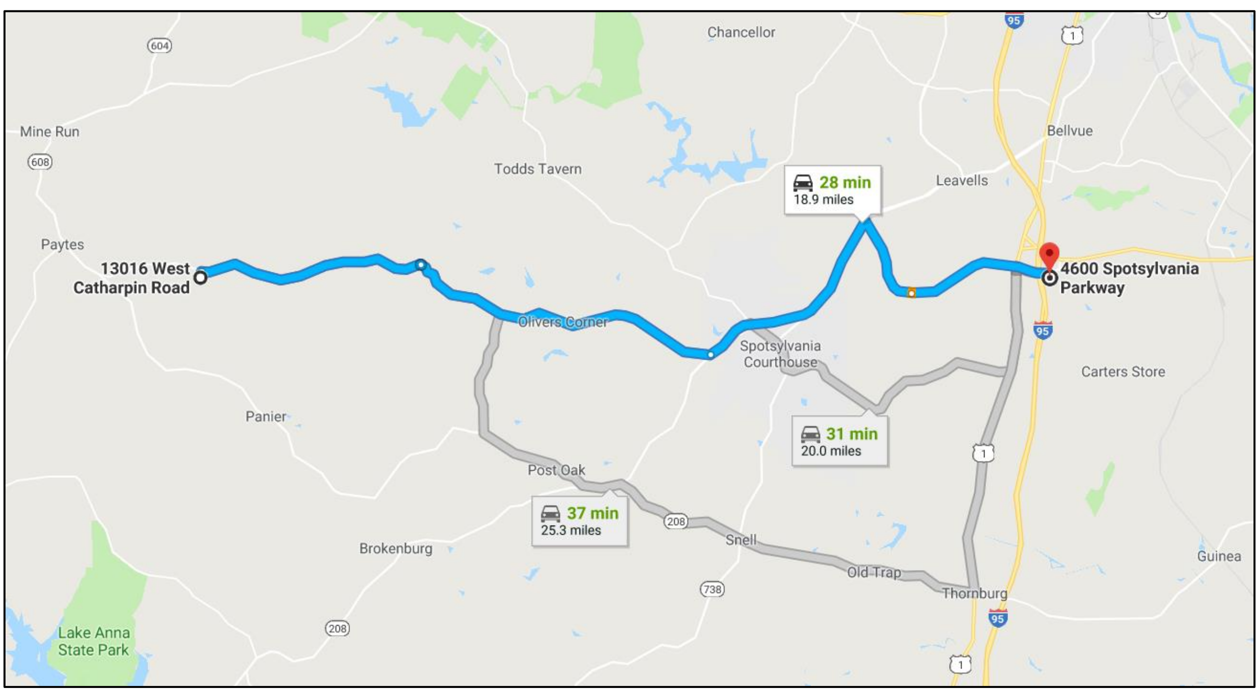
2.4 Medical Facilities

The nearest medical facility to the Project Site is:

Spotsylvania Regional Medical Center
4600 Spotsylvania Parkway
Fredericksburg, VA 22408

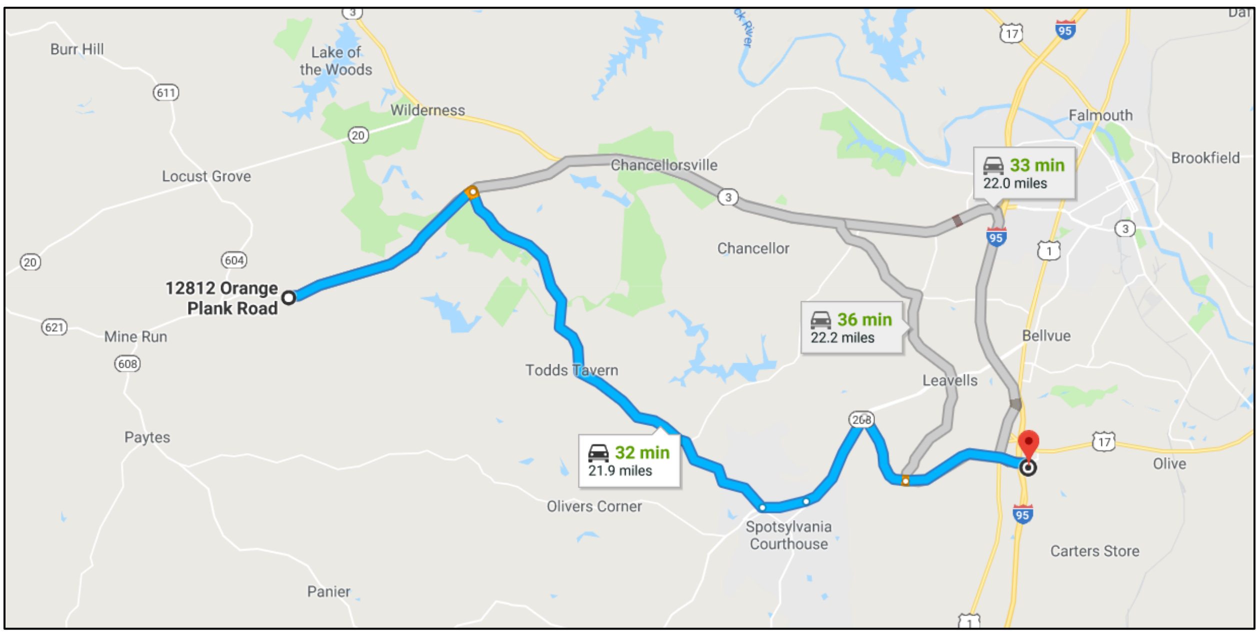
Direction from West Catharpin Road:

- Head east on West Catharpin Road
    - 4.3 mi
- Turn right onto Robert E. Lee Drive
    - 6.1 mi
- Turn left onto Courthouse Bypass (VA-208 E)
    - 4.1 mi
- Turn right onto Smith Station Road
    - 1.7 mi
- Continue onto Spotsylvania Parkway
    - 2.7 mi
- Destination is on the right



Directions from Orange Plank Road

- Head east on Orange Plank Road toward Chancellor Meadows Lane
    - 4.5 mi
- Turn right onto Brock Road
    - 9.8 mi
- Turn left onto Courthouse Bypass
    - 0.9 mi
- Continue onto Courthouse Road (VA-208 E)
    - 2.2 mi
- Turn right onto Smith Station Road
    - 1.7 mi
- Continue onto Spotsylvania Parkway
    - 2.7 mi
- Destination is on the right



3.0 HAZARDOUS MATERIAL SPILL

The hazardous materials that may be on the Project Site during operations include those usually associated with the operation and maintenance of vehicles and machinery, including diesel fuel, gasoline, hydraulic fluid, brake fluid, antifreeze, and lubricants. Other materials considered hazardous are chemicals used in portable toilets and the associated human waste. In the unlikely event of a hazardous materials spill into an Resource Protection Area (RPA), wetland, or stream, Spotsylvania County EMS and the Zoning Department shall be notified immediately.

3.1 Spill Prevention

The best defense against hazardous material spills is prevention. The following measures shall be implemented at the Project Site for spill prevention:

- All on-site personnel shall be trained to maintain and inspect their vehicles and equipment.
- All machinery found to be a potential source of a future spill shall be removed from the Project Site and repaired. Vehicles with chronic or continuous leaks must be removed from the Project Site and repaired before returning to operations. No leaking of any material from equipment or vehicles will be tolerated on the Project Site.
- On-site personnel shall make every effort to ensure compliance prior to an incident. On-site personnel are solely responsible for any spills of hazardous materials and the subsequent cleanup, disposal of waste, and restoration of any contaminated areas.
- Restrictions will be placed on all equipment refueling, servicing, and maintenance supplies and activities. All maintenance materials, oils, grease, lubricants, antifreeze, etc. shall be stored off-site. If they are required during field operations, they shall be placed in a designated area away from site activities and in an approved storage container.
- No refueling, storage, servicing, or maintenance of equipment shall take place within 100 feet of a drainage or sensitive environmental resources to reduce the potential of contamination by spills.
- No refueling or servicing shall be done without absorbent material or drip pans properly placed to contain spilled fuel.
- Any fluids drained from the machinery during servicing shall be collected in leak-proof containers and taken to an appropriate disposal or recycling facility. If these activities result in damage or accumulation of product on the soil, it must be disposed of as hazardous waste.
- Under no circumstances shall contaminated soil be added to a spoils pile and transported to a regular disposal site.
- During operations, all vehicles and equipment required on-site shall be parked or stored at least 100 feet away from rivers, streams, wetlands, known archaeological sites, and any other sensitive resource areas. All wash down activities must be accomplished away from sensitive environmental resources.

3.2 Spill Containment Equipment

The following equipment shall be at the Project Site with each construction crew in the event a spill occurs.

1. Emergency Spill Kit that includes at a minimum:
   a. Sorbent socks
   b. Disposal bags and ties
   c. Safety glasses
   d. Rubber gloves
   e. Sorbent drip pillow
   f. Sorbent pads, 18” x 18”
   g. Sorbent spill pillows, 24” x 18”
   h. Hazardous labels
   i. Bag of Lite-Dri Absorbent (or equal)
   j. Shovel and broom

2. Absorbent Pads - These pads (18" x 18") are 100% polypropylene fabrics that absorb 11 times their weight in liquids. Pads absorb 10 gallons of liquid per bale of 100 pads.

3. Absorbent Skimmers Booms - Skimmers will float indefinitely before or after saturation with oils. Skimmers are made of 100% meltdown polypropylene fill that repels water. They absorb ten times their weight and can be used in lakes, streams, or on the ground. Each skimmer has a harness kit attached that is made of yellow polypropylene rope with grommets that are used to connect skimmers. Each boom is 8-feet x 10-feet.

4. 55-gallon clean drums, lined with polypropylene material (over pack). The drum can be used to store spill response materials until needed. When a spill occurs, all soiled pads, pillows, skimmers, contaminated soil, etc. shall be placed in the drum for disposal after the cleanup is accomplished. It is the sPower's responsibility to make sure these materials are on-site at all times and personnel are trained in their use and disposal prior to spill response.

3.3 Spill Response Procedures

A formal notification process shall be initiated when a spill or potential spill is first observed. Immediate actions are necessary. The first individual who discovers a spill (spill observer) will be responsible for initiating notification and response procedures. All personnel responsible for responding to spills must have completed training in recognition and response to spills of hazardous materials. sPower is responsible for providing spill recognition and response training for all sPower project personnel.

<u>Spill Observer</u>

The first person to witness the spill shall follow these procedures:

1. Make an assessment of the incident as observed.
2. If the incident can be safely controlled, take steps to do so (e.g., turn off source of spill).
3. Notify sPower Management Team and provide as much information as possible.
4. Begin to fill out Spill Notification Checklist.

<u>sPower Operations and/or Safety Management</u>

Operations and/or Safety Managers shall follow these procedures in the event of a spill:

1. Notify Supervisors
2. Make sure all personnel are removed from the spill area.
3. Take immediate actions to minimize any threat to public safety (verify the spill area has been cordoned off).
4. Secure the source of the spill, if safely possible to do so.
5. Maintain close observation of the spill.

3.4 Vehicle and Machinery Spills

Incidents of loss of a petroleum product from equipment or vehicles shall be considered a spill. After the spill has been flagged to warn people to stay away, the volume and extent of the spill estimated, and initial notification procedures accomplished, the spill must be confined. Do not handle materials without wearing protective clothing.

Generally, follow the procedures listed below:

1. When the spill is discovered begin making notations on the Spill Notification Checklist.

2. Determine if the Spill Team Response is needed to complete cleanup.
    a. If the answer is NO, submit incident reports to Operations and/or Safety Managers
    b. If the answer is YES, go to step 3.

3. Activate the local spill response team.

4. Determine if additional cleanup contractors are necessary for a major incident.
    a. If the answer is NO and the incident is determined to be a minor spill, conduct internal cleanup, review and evaluate the cleanup, determine if the cleanup is beyond the local response team ability or equipment; if the answer is NO, complete the cleanup, restore the damaged areas, properly dispose of all waste, and submit incident reports to Operations and/or Safety Managers. If during cleanup, the incident is determined to be beyond the abilities of the local response team, hire additional contractors to help with the cleanup.
    b. If the answer is YES, hire additional contractors to help with the cleanup.

5. Arrange for proper testing and disposal of all waste if substance is unknown.

6. Closely monitor all cleanup activities.

7. Ensure proper disposal of absorbent materials, containers, and soils, as required.

8. Complete the cleanup and restore damaged areas.

9. Submit incident reports to Operations and/or Safety Managers.

Cleanup may range from very simple removal of minor spills, to installation of skimmers around large spills or between sensitive areas and spills for longer, prolonged cleanups. Cleanups can be on pavement or on soil surfaces. On-site personnel shall be trained in the proper use of the cleanup materials. All spills on pavement shall be thoroughly removed with absorbent socks, pillows, or pads and Lite-Dri (or equal) granules. After absorption, the granules shall also be removed. All materials used in cleanup, shall then become hazardous waste. Place all materials in a 55-gallon lined drum, seal it, and label the contents. The drum must then be sent to a designated disposal site. A chain of custody form must accompany the drum (provided by Disposal Company). It is strongly recommended that all contractors determine a disposal site in advance of a spill incident.

All spills on soil require the same treatment as on pavement, with the exception that contaminated soil is also part of the generated hazardous waste and must be handled as such and removed from the site.

3.5 Chemical Toilet Spill

Chemical toilets are self-contained and pose little threat to the construction site. Chemicals used in portable toilets are biodegradable and generally non-toxic to humans. However, they can pose a danger to wildlife and sensitive habitats by virtue of heavy concentration of chemical and human waste. They shall be pumped out at least one time per week. Toilets shall never be placed in or near an environmentally sensitive area. In the unlikely event that a portable toilet spills during transport or relocation, the same procedures for other hazardous material spills shall be used. Disposal of absorbent materials shall be handled the same as other spills, with proper disposal by the toilet supply company.

3.6 Reporting of Major Spills

Upon recognition of a major spill, notification is critical to immediate response. The first notification shall be given to the nearest Operations and/or Safety Managers so that appropriate spill response can begin immediately. After initial spill response has begun, notification and reporting to agency personnel shall occur. The following procedures should be followed when reporting major spills:

1. Never include information that has not been verified.
2. Never speculate as to the cause of the incident or make any acknowledgment of liability.
3. Do not delay reporting because of incomplete information.
4. Notify persons/agencies and document notification and the content of the message.
5. For spills of federal reportable quantities, in conformance with the requirements in 40 CFR parts 110,119, and 302, O&M staff shall notify the National Response Center at (800) 424-8802.
6. Complete the Spill Notification Checklist as information is confirmed.

Other agencies which may need to be consulted include, but are not limited to, the County Fire Department, Public Works Department, Highway Patrol, County Police Department, Department of Toxic Substances, OSHA, RWQCB, DEQ, and or DGIF.

3.7 Disposal of Waste

Following the cleanup of a spill, the waste, absorbent materials, protective clothing, and any soil that has been contaminated must be removed to a designated hazardous waste disposal area. All contaminated materials shall be sealed in 55-gallon drums and labeled with the contents. If the contaminant is unknown, a sample of the material must be collected and analyzed before disposal. A permit or approval in writing must be obtained prior to disposal of the drum. A copy of the permit and a chain-of-custody form (obtained from the disposal contractor or testing laboratory) must accompany the material and copies must be attached to the Spill Notification Checklist submitted to Operations and/or Safety Managers. It is advisable for contractors to establish a relationship with a disposal facility before an incident occurs. Local landfills may be able to receive some petroleum products. However, it is up to the contractor to perform sampling, testing, and coordination with landfills or a disposal company. Transporting hazardous waste is regulated by federal and state agencies under the Resource Conservation and Recovery Act (RCRA) and other statutes. The contractor is responsible for the proper disposal of all waste and understanding the responsibilities under federal and state statutes.

3.8 Final Reporting

Spill incidents that require cleanup must be reported on the Spill Notification Checklist. Notification must begin as soon as the incident occurs. The checklist shall be submitted to Operations and/or Safety Managers as soon as it is complete. Forms must be submitted no longer than five days after an incident is closed. A copy of the permit or disposal approval and the chain-of custody for the disposal must be attached to the Spill Notification Checklist. The forms shall be reviewed and filed in the contractor's file. No exceptions will be tolerated.

If a situation arises involving an unknown hazardous material, the Spill Notification Checklist can be used to report the incident. This incident may require a very different approach to removing the hazard and the contractor may be required to remove the material. The incident must still be reported by the contractor.

3.9 Follow-Up Investigation

A critique following a spill response is beneficial to evaluate the actions taken or omitted. Recommendations and suggested modifications will be made to prepare for the possibility of future spills.

3.10 Spill Notification Checklist

Spill Notification Checklists shall be provided at all construction trailers. At a minimum, the Spill Notification Checklists shall require the following information:

- Date
- Time
- Location
- Description of Spill (color, length, width, type)
- Type of Product
- Estimated Quantity
- Source of Spill (vehicle, machine, etc.)
- Describe initial containment procedures
- Weather conditions
- Note if spill reached any body of water
- Individuals notified of spill (include name, company, date, time, and response)

4.0 NATURAL DISASTERS

The Operations and/or Safety Managers will be monitoring weather daily via met stations located at the Project Site.

4.1 Flooding and Flash Floods

Flash flooding is a result of heavy localized rainfall such as that from slow moving, intense thunderstorms. Flash floods often result from small creeks and streams overflowing during heavy rainfall. These floods often become raging torrents of water which rip through river beds, or canyons, sweeping everything with them. Flash flooding can occur within 30-minutes and within six hours of a heavy rain event. In hilly terrain, flash floods can strike with little or no advance warning. Distant rain may be channeled into gullies and ravines causing flash flooding in minutes. In the event of a flash flood, the following procedures shall apply.

1. During periods of thunderstorms, always remain alert to heavy rains in your immediate area or upstream from your location. It does not have to be raining at your location for flash flooding to occur.

2. Do not drive through flooded areas. Even if it looks shallow enough to cross.

3. Do not cross flowing streams on foot where water is above your ankles.

4. Be especially cautious at night. It is harder to recognize water danger then.

5. Do not attempt to outrace a flood on foot. If you see or hear it coming, move to higher ground immediately.

6. Be familiar with the land features where you work. It may be in a low area, near a drainage ditch, or small stream.

7. Stay tuned to weather forecasts and updates for the latest statements, watches, and warnings concerning heavy rain and flash flooding in the Project Area.

8. Waiting 15 to 30 minutes, or until high water recedes, is a simple safety measure.

4.2 Tornado

Upon the issuance of a tornado warning, O&M staff will evacuate the Project Site and report to the predesignated shelter area, to be determined prior to O&M staff arrival. In the event O&M staff are outside and unable to evacuate to the shelter, the following procedure will be followed:

1. Lie flat in a nearby ditch or depression, covering the head with the hands. Be aware of the potential for flooding.

2. O&M staff are safest in a low, flat location and will be instructed to not get under an overpass or bridge.

3. O&M staff will be instructed to never try to outrun a tornado in congested areas in a vehicle. It is safest to leave the vehicle for safe shelter.

4. O&M Staff are instructed to beware of flying debris.

Following tornado or high wind events, the site facility will be evaluated by O&M personnel for damage. All repairs will be performed under standard operational procedures.

4.3 High Wind Event

In the event of a high wind advisory, all land clearing, grading, earth moving, excavation and burning activities shall cease during periods when:

- Winds are greater than 25 mph (averaged over one hour);
- Disturbed material is easily windblown; or
- Dust plums of greater than 20% or greater opacity impact public roads, occupied structures, or neighboring properties

Refer to the following table for procedures during varying wind speeds.

Wind Speed (averaged over one hour)	Action
0 – 15 mph	Normal Work
> 15 mph	Warning
25 mph	1. Civil/Mechanical work causing dust at property lines is stopped 2. Increase dust control measures 3. Increase personal protection equipment (e.g., goggles instead of standard safety glasses)
30 mph	1. Panel installation is stopped 2. Aerial lift activities are stopped
35 mph	1. All construction and maintenance activities are stopped 2. Crews evacuate from the Project Site
40 mph	1. Operational solar panels will automatically stow into the wind. Solar panels are controlled by on-site controllers and wind sensors, and the sPower Control Room in Salt Lake City, Utah.

4.4 Lighting Storm

In the event a lighting storm is within 10 – 30 miles and approaching the Project Site, the following procedures shall apply.

1. Notify Operations and/or Safety Manager, and all on-site employees.

2. Stop work safely and head to staging and laydown yards in vehicles.

3. Remain at staging and laydown yards, get update on weather conditions.

4. If storm/lighting is still approaching the Project Site, get in and stay in company or personal vehicles that have rubber tires only.

5. If safe enough to do so, take cover in on-site designated shelters.

6. Once storm passes, remain in cars/trucks for at least 30 minutes depending on passing storm severity, and wait for an "OK" from Construction Supervisors or Safety Managers in charge of monitoring the storm.

5.0 FIRE PREVENTION PLAN

5.1 Purpose and Need of Fire Prevention Plan

The purpose of this Fire Prevention Plan (FPP) is to:

- Eliminate the potential risks and/or causes of fires
- Prevent loss of life and property by fire
- Educate employees to promote a safe environment
- Be prepared should a fire occur
- Outline a procedure to follow for the safety of the individuals at the Project Site at the time of the occurrence
- Identify risk factors and hazards
- Set up proper storage procedures, training, and identification of personnel responsible for maintaining and servicing the equipment and systems at the Project Site that are used to prevent and/or control a fire

5.2 Responsibilities and Procedures

Safety is everyone's responsibility at the Project Site. All O&M staff working at the Project Site are to be trained and should know how to prevent and respond to a fire emergency. All on-site staff shall:

- Complete an on-site training program identifying the fire risks at the Project Site
- Understand the protocol and follow emergency procedures should an event occur
- Review and report potential fire hazards to the Operations and/or Safety Managers

5.3 Conditions Associated with PV Solar Arrays

While the PV panels that will be installed for the Project are not flammable, PV solar arrays present a unique challenge for fire fighters. Unlike a typical electrical or gas utility, a PV array does not have a single point of disconnect. Whereas there are disconnects that will de-energize select parts of the system. As long as the PV panels are illuminated, the individual strings of PV panels are energized and capable of producing up to 1,500 volts. This is not just limited to PV panels being illuminated by the sun; illumination by artificial light sources, such as fire department lights, or the light for the fire itself are capable of producing electrical power sufficient to cause a lock-on hazard. Below is a summary of hazards associated with firefighting activities in PV solar arrays:

- Shock hazard due to the presence of water and PV power during suppression activities
  - Outdoor related electrical enclosures may not resist water intrusion from the high-pressure stream of a fire hose
  - PV panels damaged in the fire may not resist water intrusion
  - Damaged conductors may not resist water intrusion

- Shock hazard due to direct contact with energized components
  - No means of complete electrical disconnect

Due to the hazards described above, it is not typical to practice fire suppression by means of water inundation within PV solar arrays.

5.4 Types of Fires and Procedures

In the event of a fire at the Project Site, the general procedure is as follows:

- Person discovering the fire shall immediately dispatch to the Operations and/or Safety Managers.
- Attempt to extinguish the fire if safe and possible to do so.
- **DO NOT** attempt to extinguish fire near electrical equipment (e.g., PV solar arrays or inverters) with water or other chemicals as an electric shock or arc could occur.
- Call **9-1-1** and report the following:
  - "I am reporting a fire at the Spotsylvania Solar Energy Center".
  - Provide address and exact Project Site entrance.
  - Provide location (ex: The fire is at Block H1)
  - Injuries if any and need for ambulance.
- A designated O&M employee shall meet fire fighters at the Project Site entrance and direct them to the location of the fire
- Prepare a summary of the incident as soon as possible and no later than 24 hours after the incident.

5.4.1 Small Stage Fires

Fires that are in the beginning stage and can be controlled with a fire extinguisher. An example would be a small trash can fire. In the event of a small stage fire at the Project Site:

- The person discovering the fire should immediately dispatch to the Operations and/or Safety Managers and O&M staff.
- Call **9-1-1** and report the following:

- "I am reporting a fire at the Spotsylvania Solar Energy Center".
    - Provide address and exact Project Site entrance.
    - Provide location (ex: The fire is at Block H1)
    - Injuries if any and need for ambulance.
- All non-essential personnel should be removed from the hazard area.
- All on-site vehicles are required to carry fire extinguishers. Fire extinguishment with a fire extinguisher or other means should be attempted if the person has been trained in the use of fire extinguishers and can do so without placing themselves in danger.
- The Operations and/or Safety Managers shall respond to the scene and determine if external resources or an evacuation is necessary. In the event of an evacuation, Operations and/or Safety Managers will recruit/dispatch employees to assist with the evacuation and, have the Operations and/or Safety Managers issue the following statement over the radio: "Attention, there is a fire emergency at (location name). Please evacuate (the affected area) and report to (designated meeting area).
- At this point, O&M staff in the affected area will stop work immediately, take steps to safely shut down equipment, exit the evacuation area, and report to the designated meeting area.
- The Operations and/or Safety Managers will then take steps to ensure that no employee re-enters the evacuated area until the Fire Department arrives and assumes command.
- The Operations and/or Safety Managers will issue an "All Clear" only when the Fire Department informs them that it is safe to do so.

5.4.2 Large Stage Fires

In the event of a large stage fire at the Project Site:

- The person discovering the fire should immediately contact the Operations and/or Safety Managers. The Safety Manager shall call **9-1-1** to report the fire.
- Call **9-1-1** and report the following:
    - "I am reporting a fire at the Spotsylvania Solar Energy Center".
    - Provide address and exact Project Site entrance.
    - Provide location (ex: The fire is at Block H1)
    - Injuries if any and need for ambulance.
- O&M staff should be removed from the immediate danger area in anticipation of an evacuation.
- The Operations and/or Safety Managers shall respond to the scene and ensure that the fire department has been dispatched. Spotsylvania County Fire, Rescue and Emergency Management will be responding to **9-1-1** calls during operations. They will then determine evacuation needs, recruit/dispatch employees to assist with the evacuation and, have the Operations and/or Safety Managers issue the following statement over the radio: "Attention, there is a fire emergency at (location name). Please evacuate (the affected area) and report to (designated meeting area).
- At this point, O&M staff in the affected area shall stop work immediately, take steps to safely shut down equipment, exit the evacuation area, and report to the designated meeting area.
- In this scenario, fire extinguishers are to be used for escape purposes only.

- The Operations and/or Safety Managers will take the necessary steps to ensure that no O&M staff re-enters the evacuated area until the Fire Department arrives and assumes command.
- No employee is required or permitted to place themselves in harm's way in order to facilitate extinguishment, evacuation, or rescue. All rescue operations will be performed by trained professionals upon their arrival.
- The Operations and/or Safety Managers will issue an "All Clear" only when the Fire Department informs them that it is safe to do so.

5.4.3 Vegetation Fires

Most likely to be caused by a spark from a nearby piece of equipment or flying ember from off-site. While combustible materials (e.g., mulch and low-lying vegetation) will be managed at the Project Site by sPower's O&M staff, ignition of the ground cover could result in a fast moving, but lower intensity fire that burns in a patchy manner beneath the PV solar arrays. Vegetation fires would be relatively short in duration as vegetative fuels are consumed rapidly. There would not be a sustained source of heat and or flame as there would be with surrounding wild fires. In the event of a vegetation fire near the PV solar arrays, the following procedures apply:

- Person discovering the fire shall immediately dispatch to the Operations and/or Safety Managers.
- **DO NOT** attempt to extinguish fire near electrical equipment with water or other chemicals as an electric shock or arc could occur.
- If possible, safely attempt to shut down power at the inverter using the DC disconnect.
- Let the fire burn vegetation and self-extinguish.
- If the fire continues away from the PV solar arrays or inverters, attempt to extinguish flames.
- Call **9-1-1** and report the following :
    - "I am reporting a fire at the Spotsylvania Solar Energy Center".
    - Provide address and exact Project Site entrance.
    - Provide location (ex: The fire is at Block H1)
    - Injuries if any and need for ambulance.
- A designated O&M employee shall meet fire fighters at the Project Site entrance and direct them to the location of the fire.

5.4.4 Inverter Fires

In the event of an inverter fire at the Project Site:

- Person discovering the fire shall immediately dispatch to the Operations and/or Safety Managers.
- Immediately contact sPower Control Room in Salt Lake City, Utah to notify them of the fire and instruct them to open the circuit with the inverter in it to isolate it from the grid.
- **DO NOT** attempt to extinguish fire near electrical equipment with water or other chemicals as an electric shock or arc could occur.
- Call **9-1-1** and report the following:

- “I am reporting a fire at the Spotsylvania Solar Energy Center”.
- Provide address and exact Project Site entrance.
- Provide location (ex: The fire is at Block H1)
- Injuries if any and need for ambulance.

- A designated O&M employee shall meet fire fighters at the Project Site entrance and direct them to the location of the fire.
- If possible, O&M staff shall safely attempt to shut down power at the inverter using the DC disconnect.
- O&M staff protect surrounding areas from flying embers with fire extinguishers.
- Provide Safety Data Sheets (SDS) for the skid if needed.

5.5 Fire Department Access

Access for County Fire, Rescue, and Emergency Management will be provided at all Project Site entrances punch code key boxes. If a fire occurs while sPower’s O&M staff are present at the Project Site, the O&M staff shall provide emergency dispatchers with the exact address and location of the nearest site access point and meet fire fighters at the entrance to escort them to the fire.

Internal site access roads will consist of compacted dirt roads. These access roads will provide direct access to each of the Project’s inverters and transformers.

Access to all areas of the Project Site are provided via access aisles. Access aisles are the cleared areas located between individual rows of the PV solar arrays. Access aisles consists of unimproved native material and are not suitable for all emergency services vehicles. However, access aisles do provide emergency responders with access routes to all areas of the Project Site via walking from a nearby access road or by use of 4x4 vehicles.

5.6 Minimizing Fire Risks

sPower’s O&M staff shall be responsible for implementing the following preventative measures for Class A, B, and C combustibles:

- <u>Class A Combustibles</u> – consist of common material (wood, paper, cloth, rubber, and plastic) that can act as fuel and are found on most work sites.
  - Dispose of waste daily.
  - Use trash receptacles with covers.
  - Keep work areas clean and free of combustible materials.
  - Store materials in the proper storage containers.
  - Conduct periodic checks of the Project Site to make sure combustibles are being handled correctly.
  - Water and multi-purpose dry chemicals (ABC) are approved fire extinguishing agents for Class A Combustibles.

- Class B Combustibles – consist of flammable and combustible liquids (oil, grease, tar, oil-based paints and lacquers), flammable gases, and flammable aerosols.

  - Only use approved pumps (with suction from the top) to dispense liquids from tanks, drums, barrels, or similar containers (or use approved self-closing valves or faucets).
  - Do not dispense Class B flammable liquids into a container unless the nozzle and container are electrically interconnected by contact or bonding wire. Either the tank or container must be grounded.
  - Store, handle, and use Class B combustibles only in approved locations where vapors are prevented from reaching ignition sources such as heating or electric equipment, open flames, or mechanical or electric sparks.
  - Do not use a flammable liquid as a cleaning agent inside a building (the only exception is in a closed machine approved for cleaning with flammable liquids).
  - Do not use, handle, or store Class B combustibles near exits, stairs, or any other areas normally used as exits.
  - Do not weld, cut, grind, or use unsafe electrical appliances or equipment near Class B combustibles.
  - Do not generate heat, allow an open flame, or smoke near Class B combustibles.
  - Know the location of and how to use the nearest portable fire extinguisher rated for Class B fire.
  - Water should not be used to extinguish Class B fires caused by flammable liquids, as it can cause the burning liquid to spread, making the fire worse. To extinguish a fire caused by flammable liquids, exclude the air around the burning liquid.
  - Carbon dioxide and multi-purpose dry chemicals (ABC) are approved fire extinguishing agents for Class B Combustibles.

- Class C Combustibles – consist of energized electrical equipment.

  - **ALWAYS** de-energize the circuit supplying the fire, and then use a non-conductive extinguishing agent such as carbon dioxide or multi-purpose dry chemicals (ABC).
  - **DO NOT** use water, form, or other conductive agents when fighting Class C Combustibles.
  - Once the electricity is shut down to the equipment involved, the fire generally becomes a standard combustible fire.
  - Use only appropriately rated fuses per manufacture's specifications.
  - Check all electrical equipment to ensure it is properly grounded and insulated.
  - Ensure adequate spacing while performing maintenance.
  - Check wiring to ensure no damage to cables or connections.

5.7 Employee Training and Education

Fire procedures are to be posted at the Project Site on a bulletin board along with the OSHA compliance postings, first aid, and site-specific project information. The bulletin board is to be located at the O&M Building located on-site.

O&M staff shall be trained in the practices of the FPP relevant to their duties. O&M staff shall be trained and equipped to extinguish small fires to prevent them from growing into more serious threats. Confirm all O&M staff understand the function and elements of the FPP, including potential emergencies, reporting procedures, evacuation plans, and shutdown procedures. Review any special hazards that might occur at the Project Site, such as flammable materials, fuel storage, toxic chemicals, and water reactive substances.

Fire safety training will occur during the site safety training. O&M staff are required to undergo training prior to starting work. Training shall include:

- Employee roles and responsibilities.
- Recognition of potential fire hazards.
- Alarm system and evacuation routes.
- Location and operation of manually operated equipment (fire extinguishers).
- Emergency response procedures.
- Emergency shutdown procedures.
- Information regarding specific materials to which employees may be exposed.
- Review OSHA requirements contained in 29 CFR 19010.38, Emergency Action Plans.
- Review OSHA requirements contained in 29 CFR 1910.39, Fire Prevention Plans.
- The location of the company FPP and how it can be accessed.
- Good fire-prevention housekeeping practices and equipment maintenance.

The Operations and/or Safety Managers are responsible for fire safety training. Written documentation of the training received by each employee must be maintained.

5.8 Site Maintenance and Housekeeping

- Fire extinguishers shall be inspected monthly.
- Fire extinguishers shall not be obstructed and should be in conspicuous locations.
- Combustible material shall not be stored in mechanical rooms, electrical equipment rooms, or the SCADA buildings.
- Outside dumpsters shall be kept at least five (5) feet away from combustible materials and the lid should be kept closed.
- Storage is not allowed in electrical equipment rooms, or near electrical panels.
- Electrical panel openings must be covered.
- Power strips must be plugged directly into an outlet and not daisy-chained and should be for temporary use only.
- Extension cords and flexible cords should not be substituted for permanent.

5.9 Equipment Fire Safety

- All internal combustion engines, both stationary and mobile, shall be equipped with spark arresters. Spark arresters shall be in good working order.

- Light trucks and cars with factory-installed (type) mufflers shall be used only on roads where the roadway is cleared of vegetation. These vehicle types shall maintain their factory-installed (type) mufflers in good condition.
- Equipment parking areas and small stationary engine sites shall be cleared of all extraneous flammable materials.
- The project proponent shall make an effort to restrict the use of chainsaws, chippers, vegetation masticators, grinders, drill rigs, tractors, torches, and explosives to periods outside of the official fire season. When the above tools are used, water tanks equipped with hoses, fire rakes, and axes shall be easily accessible to personnel.

6.0 Heat Illness Prevention Plan

These procedures provide steps applicable to most outdoor work settings and are essential to reducing the incidence of heat related illnesses. In working environments with a higher risk for heat illness (e.g., during a heat wave, hot summer months exceeding 95 degrees Fahrenheit, or other severe working or environmental conditions), it is sPower's duty to exercise greater caution and ensure these procedures are implemented, including additional protective measures beyond what is listed in this document, as needed to protect employees affected by high heat conditions.

When the temperature exceeds 95 degrees, high heat procedures begin, the Operations and/or Safety Managers will hold short tailgate meetings to review the weather report, reinforce heat illness prevention with all workers and provide reminders to drink water frequently, to be on the lookout for signs and symptoms of heat illness, and inform them that shade can be made available upon request.

6.1 Definitions

"Acclimatization" means temporary adaptation of the body to work in the heat that occurs gradually when a person is exposed to it. Acclimatization peaks in most people within four to fourteen days of regular work for at least two hours per day in the heat.

"Heat Illness" means a serious medical condition resulting from the body's inability to cope with a particular heat load, and includes heat cramps, heat exhaustion, heat syncope, and heat stroke.

"Environmental risk factors for heat illness" means working conditions that create the possibility that heat illness could occur, including air temperature, relative humidity, radiant heat from the sun and other sources, conductive heat sources such as the ground, air movement, workload severity and duration, protective clothing and personal protective equipment worn by employees.

"Personal risk factors for heat illness" means factors such as an individual's age, degree of acclimatization, health, water consumption, alcohol consumption, caffeine consumption, and use of prescription medications that affect the body's water retention or other physiological responses to heat.

"Shade" means blockage of direct sunlight. One indicator that blockage is sufficient is when objects do not cast a shadow in the area of blocked sunlight. Shade is not adequate when heat in the area of shade defeats the purpose of shade, which is to allow the body to cool. For example, a car sitting in the sun does not provide acceptable shade to a person inside it, unless the car is running with air conditioning. Shade may be provided by any natural or artificial means that does not expose employees to unsafe or unhealthy conditions, and that does not deter or discourage access or use.

"Temperature" means the temperature in degrees Fahrenheit obtainable by using a thermometer to measure the outdoor temperature in an area where there is no shade. While the temperature measurement must be taken in an area with full sunlight, the thermometer should be shielded while taking the measurement, e.g., with the hand or some other object, from direct contact by sunlight.

"Provision of water" Employees shall have access to potable drinking water. The water will be fresh, pure, suitably cool, and provided to employees free of charge. The water shall be located as close as practicable to the areas where employees are working. Where drinking water is not plumbed or otherwise continuously supplied, it shall be provided in sufficient quantity at the beginning of the work shift to provide one quart per employee per hour for drinking for the entire shift. Employers may begin the shift with smaller quantities of water if they have effective procedures for replenishment during the shift as needed to allow employees to drink one quart or more per hour. The frequent drinking of water shall be encouraged.

6.2 Provisions of Water (Water Distribution Plan)

Bottled water is provided for all on-site personnel. All sPower sub-contractors are required to provide a written Heat Illness and Water Distribution Plan, as well as the required potable water and ice for their personnel on site daily.
Means and Methods for Providing Drinking Water to All Employees

1. The on-site manager will ensure that there is a minimum of two quarts per employee per hour in the work area at all times during the shift. This can be achieved by having bottled water chilled in coolers or using 5 to 10-gallon jugs.

2. If water jugs or bottled water is unavailable, all employees will be furnished a camelback for drinking water purposes prior to going to work.

3. When the temperature exceeds 90 degrees the employees will ensure an ample supply of water is readily available.

4. The on-site manager must insure that the drinking water moves as the work does.

5. The on-site manager is responsible for properly cleaning water jugs at a minimum every shift. Cleaning must be in accordance with the water jug cleaning procedure. If camelbacks are in use, the employee is responsible for care and cleaning.

6. The on-site manager will announce all drinking water locations in the daily tool box meeting. When the temperature is expected to be over 90 degrees the supervisor will discuss signs and symptoms, hydration, and other pertinent heat illness topics.

7. When the temperature is 95 degrees or more, the on-site manager or designee will increase the number of mandatory water drinking breaks.

8. During the site-specific safety orientation, the importance of frequently drinking water will be stressed.

6.3 Accessing Shade

1. The on-site manager will be given enough shade tents to cover 75 percent of their employees at the same time.

2. The on-site manager will also be given picnic tables, chairs, or benches so the employees will have a place to sit under the shade tent.

3. The interior of a vehicle may only be considered a shaded area if the air conditioning is both on and works properly.

4. The on-site manager will make the employees aware of the shaded locations in the daily tool box meeting. They will also make sure that the shade areas move with the workforce.

6.4 Handling a Heat Wave

During a heat wave or heat spike (increase in afternoon temperature of more than 10 degrees) the Project Site will be closed, and the work will need to be rescheduled or done at different hours. If the work can't be completed at a different time, the on-site manager will hold an emergency tailgate meeting to inform all employees of the heat conditions, emergency response procedures, and mitigation techniques.

6.4.1 High Heat Procedures

1. The on-site manager will ensure effective communication by voice, observation, or electronic means is maintained so that employees can contact a supervisor when necessary.

2. Employees will monitor other employees for alertness and signs and symptoms of heat illness.
3. Fellow employees will police each other to ensure their co-workers are drinking water frequently throughout the shift. New employee will be assigned a "buddy" or experienced coworker for the first 14 days of the employment.

6.4.2 Acclimatization

Acclimatization is the temporary and gradual physiological change in the body that occurs when the environmentally induced heat load to which the body is accustomed is significantly and suddenly exceeded by sudden environmental changes. In more common terms, the body needs time to adapt when temperatures rise suddenly, and an employee risks heat illness by not taking it easy when a heat wave strikes or when starting a new job that exposes the employee to heat to which the employee's body hasn't yet adjusted.

Inadequate acclimatization can imperil anyone exposed to conditions of heat and physical stress significantly more intense than what they are used to. Employers are responsible for the working conditions of their employees, and they must act effectively when conditions result in sudden exposure to heat their employees are not used to.

1. sPower Team will monitor the weather and in particular be on the lookout for sudden heat wave(s) or increases in temperatures to which employees haven't been exposed to for several weeks or longer.

2. During the hot summer months, the work shift will start at first light.

3. For new employees, on-site managers will try to find ways to lessen the intensity of the employees work during a two-week break-in period (such as scheduling slower paced, less physically demanding work during the hot parts of the day and the heaviest work activities during the cooler parts of the day (early-morning or evening). Steps taken to lessen the intensity of the workload for new employees will be documented.

4. New employees will remain vigilant and alert for the presence of heat related symptoms.

5. New employees will be assigned a "buddy" or experienced coworker to watch each other closely for discomfort or symptoms of heat illness.

6. O&M teams will observe closely (or maintain frequent communication via phone or radio) and be on the lookout for possible symptoms of heat illness.

7. sPower site orientation for employees and supervisors will include the importance of acclimatization, how it is developed and how these company procedures address it.

6.4.3 Alternate High Heat Work Schedule

When ambient temperatures remain at and exceed 95 degrees the Operations and/or Safety Managers shall discuss revisions to the work schedule (start time, end-of-shift time, multiple shifts with varying start times). When the alternate high heat schedule is in effect, personnel will meet each morning to go over the following items:

Heat Index 1 Heavy physical work with acclimated worker	**RESPONSE**	**Heat Index 2** Moderate or lite physical work with

		unacclimated worker
89 – 95°F	• Supply water to workers on an "as needed basis"	77 – 84°F
96 – 102°F	• Post Heat Stress Alert Notice • Encourage workers to drink extra water • Start recording hourly temperature and relative humidity	85 – 93°F
103 – 108°F	• High Heat Procedures in effect notice • Notify workers to consume more water • Ensure workers are trained to recognize symptoms	94 – 99°F
109 – 111°F	• Provide 15 minutes relief per hour • Provide adequate cool water (50 -59°F) • At least 1 cup (240 ml) water every 20 minutes • Workers with symptoms should seek medical attention	100 – 102°F
112 – 115°F	• Provide 30 minutes relief per hour in addition to the provisions listed previously.	103 – 108°F
116 – 120°F	• If feasible, provide 45 minutes relief per hour in addition to the provisions listed previously • If a 75% relief period is not feasible then stop work until the Heat Index is 107°F or less	109 – 111°F
121°F+	• Stop work until the Heat Index is 107°F or less	112°F+

6.4.4 Handling a Sick Employee

1. When an employee displays possible signs or symptoms of heat illness, the sPower Operations Manager will be notified. An employee trained in first aid will check the sick employee and determine whether resting in the shade and drinking cool water will suffice or if emergency service providers will need to be called.

2. Do not leave a sick worker alone in the shade, as he or she can take a turn for the worse!

3. Call emergency service providers immediately if an employee displays signs or symptoms of heat illness (loss of consciousness, incoherent speech, convulsions, red and hot face), does not look OK or does not get better after drinking cool water and resting in the shade.

4. While the ambulance is in route, initiate first aid (cool the worker: place in the shade, remove excess layers of clothing, place ice pack in the armpits and join area and fan the victim).

5. Do not let a sick worker leave the site, as they can get lost or die (when not being transported by ambulance and treatment has not been started by paramedics) before reaching a hospital.

6. If an employee does not look OK and displays signs or symptoms of severe heat illness (loss of consciousness, incoherent speech, convulsions, red and hot face), and the worksite is located more than 20 min away from a hospital, call emergency service providers, communicate the signs and symptoms of the victim and request Air Ambulance.

6.4.5 Procedures for Employee and Supervisory Training

1. sPower will ensure that all supervisors are trained prior to being assigned to supervise other workers. Training will include this company's written procedures and what steps supervisors will follow when employees' exhibit symptoms consistent with heat illness.

2. sPower will ensure that all employees and supervisors are trained prior to working outside. Training will include the site-specific orientations, lunch and learns, and tool box topics.

3. sPower Safety Manager will train employees on the steps that will be followed for contacting emergency medical services, including how they are to proceed when there are non-English speaking workers, how clear and precise directions to the site will be provided as well as stress the need to make visual contact with emergency responders at the nearest road or landmark to direct them to the worksite.

6.4.6 Procedures for Emergency Response

1. Prior to assigning a crew to a particular worksite, the Operations Manager will ensure that a qualified, appropriately trained and equipped person will be available at the Project Site to render first aid if necessary.

2. All on-site personnel will carry cell phones or other means of communication, to ensure that emergency medical services can be called and check that these are functional at the worksite prior to each shift.

3. When an employee is showing symptoms of possible heat illness, the supervisor will take immediate steps to keep the stricken employee cool and comfortable once emergency service responders have been called (to reduce the progression to more serious illness).

4. During a heat wave or hot temperatures, workers will be reminded and encouraged to immediately report to their supervisor any signs or symptoms they are experiencing.

sPower site specific orientation for employees and supervisors will include every detail of these written emergency procedures.

Appendix A

Emergency Contact Information

Division	Name, Title	Email
Fire Prevention	Philip M. Sullivan, Deputy Fire Marshal	psullivan@spotsylvania.va.us
EMS Health and Safety	Mike Grubb, Division Chief	mgrubb@spotsylvania.va.us
Emergency Management	Matthew Embrey, Division Chief	membrey@spotsylvania.va.us

The following table lists the County Fire and Rescue Stations that are nearest to the Project Site.

County Fire and Rescue Station	Address	Phone Number	Distance from Project Site
Fire Company/Rescue Station 7 (Wilderness)	10501 Orange Plank Road, Spotsylvania, VA 22553	Fire: (504) 507-7970/7971 Rescue: (540) 507-7952/7953	3.30 miles northeast of Site A
Fire Company/Rescue Station 9 (Belmont)	7100 Belmont Road, Mineral, VA 23117	Fire: (540) 507-7974/7975 Rescue: (540) 507-7956/7957	4.30 miles southwest of Site B
Fire Company/Rescue Station 2 (Brokenburg)	11700/11701 Volunteer Lane, Spotsylvania, VA 22553	(540) 507-7942/7943	5.75 miles southeast of Site C
Fire Company/Rescue Station 5 (Chancellor)	6204 Plank Road, Fredericksburg, VA 22407	Fire: (540) 507-7966/7967 Rescue: (540) 507-7948/7949	6.55 miles northeast of Site A

The following table lists the medical facilities that are nearest to the Project Site.

Medical Facility	Address	Phone Number	Available Services	Distance from Project Site
Spotsylvania Regional Medical Center	4600 Spotsylvania Parkway Fredericksburg, VA 22408	(540) 498-4000	Emergency Services	13 miles east of Site A
Fredericksburg Medical Center (Kaiser Permanente)	1201 Hospital Drive Fredericksburg, VA 22401	(540) 368-3700	Urgent Care Services	13 miles northeast of Site A
Mary Washington Hospital	1001 Sam Perry Boulevard, Fredericksburg, VA 22401	(540) 741-1100	Emergency Services	13.23 miles northeast of Site A

The following table lists the Sheriff and Animal Control Facilities contacts for the Project.

Local Police and Sheriff Station	Address	Phone Number	Distance from Project Site
Spotsylvania Sheriff	9119 Dean Ridings Ln, Spotsylvania Courthouse, VA 22553	(540) 507-7200	10 miles east of Site A
Orange County Sheriff's Office	11350 Porter Rd, Orange, VA 22960	(540) 672-1200	15.4 miles west of Site C
Fredericksburg Police Department	2200 Cowan Blvd, Fredericksburg, VA 22401	(540) 373-3122	18.9 miles northeast of Site A
Spotsylvania Animal Control	450 Tv Dr, Fredericksburg, VA 22408	(540) 582-7115	12 miles east of Site A

The following table lists the sPower contacts for the Project.

Description	Name	Phone Number
sPower Safety Manager	Terry Barnhill	(661) 371-6019
sPower Operations and Maintenance Director	Robb Wilson	(520) 304-1544
sPower Operations Manager	TBD	TBD
sPower 24-Hour Control Room	Control Room	(855) 679-3553

[1] TBD contacts will be provided prior to construction.

Appendix B

Site Access Routes

(addresses to be provided prior to operation)

From: Patrick White
Sent: Tuesday, November 27, 2018 12:02 PM
To: Daniel Menahem
Cc: Wanda Parrish; Jay Cullinan; Matt Embrey; Phil Sullivan; Alexandra Spaulding; David Ansell
Subject: RE: More answers

Thanks Daniel, sharing w/ the team.

From: Daniel Menahem [mailto:dmenahem@spower.com]
Sent: Tuesday, November 27, 2018 11:25 AM
To: Patrick White <PWhite@spotsylvania.va.us>
Subject: More answers

Patrick

I can't find your original email but you asked the following (with answers):

- Detail the Lighting Protection Measures (to include requirements for grounding and surge protection for solar arrays and inverters).
  The project design will utilize standard solar industry equipment and design standards including IEC 62305 Standard - *Protection against lightning, provides general principles to be followed for protection of structures against lightning, including their installations and contents, as well as persons.* The PV racking, all related equipment and systems, including the fence are grounded as required for protection. All structures shall be connected to the common grounding network, and this will provide a low resistance path for the strike to the ground as the common grounding network will have more than several miles of connected buried bare copper conductor.
- What is the maximum speed that will the solar panels will hold up in a hurricane?
  The panel themselves are rated for over 2000 Pascals of pressure and have gone through extensive testing to prove their durability. The module manufacturer may have more detail for you on the types of testing performed.

Daniel Menahem | Sr Manager, Solar Development
O: 801.679.3513
M: 202.390.7772

S•POWER
Sustainable Power Group
2180 South 1300 East, Suite 600
Salt Lake City, UT 84106
www.sPower.com