The Effect of Photovoltaic Nanomaterial Roofing on Harvested Rainwater Quality

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Abstract

The global freshwater and energy crisis have prompted worldwide investments in rainwater harvesting and solar energy systems. As the implementation of these two systems develops concurrently, they can easily become integrated into one rooftop structure. Photovoltaic systems have the potential to leach heavy metals and other toxins from newly installed, broken or aged modules. Since the type of roofing material used for rainwater harvesting has been shown by several studies to affect the quality of the harvested rainwater, the use of solar panels on rooftops as catchment systems may pose a health risk to consumers. Hazardous materials leached from solar panels can alter the water quality of the harvested rainwater. This paper presents a laboratory-scale investigation of the effect of new and aged photovoltaic surfaces on the quality of harvested rainwater and will assess if solar panel systems can become significant sources of contamination in harvested rainwater.

Background and Problem Statement

As the human demand for drinking grows, global freshwater resources are diminishing. The World Bank estimates that the worldwide demand for water is doubling every 21 years. In fact, by 2050, the United Nations predicts that more than 2 billion people will live in water scarce areas (Glenn, 2006). In the state of Texas, extraction of groundwater has been increasing for the last 65 years, as a result of economic and population growth, and will continue to grow until the year 2050 when these groundwater resources will dry up (Loáiciga et al., 2000). The water shortage crisis has triggered many regions in the United States, including Texas, to begin investing in rooftop rainwater harvesting systems to supplement these dwindling freshwater resources. Furthermore, the global water crisis is amplified by current fossil fuel and nuclear energy systems, motivating the need to for renewable energy technologies that do not consume as much water

The depletion of non-renewable sources of energy, like coal, oil and natural gas, and climate change brought on the global energy crisis, which prompted the investment in renewable energy resources, like solar energy. Solar energy technologies offer many environmental benefits, such as reduction of greenhouse gas emissions and reclamation of degraded land that can be used for solar harvesting (Tsoutsos et al., 2005). Solar energy technologies also provide many socioeconomic benefits, including regional energy independency, creation of jobs, diversification of the energy supply, and energy in developing countries (Tsoutsos et al., 2005). However, there are also many negative environmental and health impacts of solar energy technologies.

Health hazards can be associated with the manufacturing of photovoltaic cells. Humans can be exposed to hazardous substances, such as toxic and explosive gases, corrosive liquids and carcinogenic compounds, used in the manufacturing process (Fthenakis and Moskowitz, 2000). Humans can be exposed to these toxic materials via inhalation, ingestion, or absorption through the skin (Moskowitz, 1995). These chemicals can be released from the leaching or combustion of modules (EPRI, 2003). Furthermore, indirect human exposure is also possible through contamination of the environment, such as air, drinking water sources, and biota (Fthenakis and Moskowitz, 2000).

Installed rooftop photovoltaic systems can also present human and environmental risks. Toxic chemicals, mainly heavy metals, such as cadmium and selenium, can leach from broken, weathered and/or aged modules that are still in service or after disposal (EPRI, 2003). United States Environmental Protection Agency (USEPA) Toxicity Characteristic Leaching Procedure (TCLP) is used to test the leaching from solar panels. Current-generation Cadmium telluride (CdTe), copper indium diselenide (CIS), and amorphous silicon thin-film solar panels pass the TCLP test (Cummingham, 1998). However, these leaching tests are tested only on new solar panels, but little work has been carried out on the leaching from broken, weathered and/or aged solar panels, and leaching data are not available for other types of photovoltaic modules.

Accidental rooftop fires or combustion of expended solar panels at municipal solid waste incinerators can produce toxic fumes, affecting nearby populations and environments (Moskowitz, 1995). Furthermore, spent solar modules disposed of at landfills can become a source of contamination in local soil environments, groundwaters, and surface waters (EPRI, 2003). To our knowledge, little research has been carried out on the leaching of heavy metals and other toxic compounds from spent solar panels at landfills.

Toxic chemicals from the manufacturing, usage, and disposal of solar energy technologies can also affect the biota in the local environments. The National Institute of Environmental Health Studies (NIEHS) revealed that the systemic and reproductive systems in rats were affected through direct ingestion of maximum tolerable doses of toxic compounds from solar panels; and the pulmonary system was affected through the inhalation of these compounds (EPRI, 2003). There exists a need for a balance between higher efficiency of solar panels and lower environmental impacts. Understanding the environmental impacts of these solar modules will motivate the development of more environment-friendly materials with similar or even higher energy performance.

Since rooftop rainwater harvesting can be incorporated with a solar energy capture system to alleviate both the water and energy crisis, there exists a need for the evaluation of water quality runoff from installed solar panels. Photovoltaic technologies are becoming more affordable for residential usage. The environmental and health impacts of rising installations of solar panels at the household level coupled with the installation of rooftop rainwater harvesting systems to combat regional water shortages need to be studied.

Research Objective

Chang et al. (2004) found that the type of roofing material used for rainwater harvesting affects the quality of the harvested rainwater. Toxic compounds, such as heavy metals, may leach from broken solar panels (EPRI, 2003). An integrated solar energy and rainwater harvesting system can result in changes in the water quality of the harvested rainwater (i.e., pH, concentration of metals, total suspended solids (TSS)), and their presence in the harvested rainwater can also pose a threat to human health. Exposure to heavy metals, such as cadmium, leached from solar panels has been found to disrupt the respiratory system in rats, mice, monkeys, rabbits and hamsters (Fthenakis et al., 1999). Therefore, consumption of rainwater harvested from a photovoltaic rooftop might pose a human health risk. To our knowledge, no one has studied the impact of a photovoltaic rooftop on harvested rainwater quality. Therefore, the objective of this study is to understand how the use of photovoltaic panels as the catchment surface impacts the quality of the harvested rainwater. This objective will be addressed through the use of laboratory-scale solar panel roofs.

Materials and Methodology

This research project focuses on runoff from photovoltaic cells, which have the potential to contaminate rainwater in the rooftop collection system by changing the water quality and leaching heavy metals into the captured rainwater. A lab-scale roof system is used in these studies. The lab-scale roof system (Figure 1) consists of a 4” by 4” solar panel roof coupon set up on a stand angled at 18.4 degrees, which is typical of most rooftops.

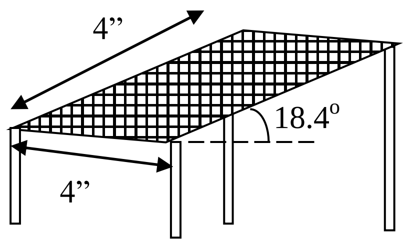

Figure 1: Lab-scale roof

Synthetic rainwater (Table 1) was synthesized for these experiments. The synthetic rainwater consisted of typical concentrations of anions and cations found in rainwater. The solution was adjusted to a typical rainwater pH of 6.5, using sodium hydroxide. The rainwater formula was adapted from Jones and Edwards (1993).

Table 1: Synthetic rainwater formula

Chemical	*Concentration (μmol/L)*	*Concentration (g/L)*
NaCl	96	5.61
K_2SO_4	10	1.74
$CaCl_2$	5	0.555
$MgCl_2$	6	0.571
NH_4NO_3	15	1.20
KH_2PO_4	0.1	0.0136

1.5L of synthetic rainwater was pumped at 13 mL/min through 23 syringes, and re-circulated for a period of 24 hours to stimulate a 10-year storm event (Figure 2).

(a) (b) (c)

Figure 2: (a) Lab-scaled rainwater runoff stimulator with peristaltic pump. (b) Roof coupon set-up. (c) 23 syringes through which synthetic rainwater dripped to stimulate rain event

After the 24-hour re-circulation of the synthetic rainwater, the runoff from the solar panels was analyzed for several water quality indicators: pH, total suspended solids, turbidity, selected metals, nitrite, and nitrate (Standard Methods, 2005). Metals concentrations were determined using Inductively Coupled Plasma/Mass Spectrometry

(ICP/MS). All of these measurements, except for the metals analysis, were performed in the Environmental and Water Resources Engineering laboratories at the University of Texas at Austin. Duplicate experiments were performed on the photovoltaic panel, and each water quality indicator was measured in triplicate.

These experiments were carried using amorphous silicon thin-film/flexible solar panels. These 3.7” by 5.9”4.8V 100mA flexible solar panels (SolMaxx-Flex-4_8V100mA) were purchased from Silicon Solar Inc., Centennial, CO (Figure 3). These flexible solar panels were chosen for the experiments because they are becoming increasingly popular among residential households due to lower manufacturing costs and ease of installation. These solar cells are produced by depositing a thin film of silicon on a durable, paper-thin flexible polymer substrate. For extended outdoor use, the solar panels have aluminum frames to protect the edges.

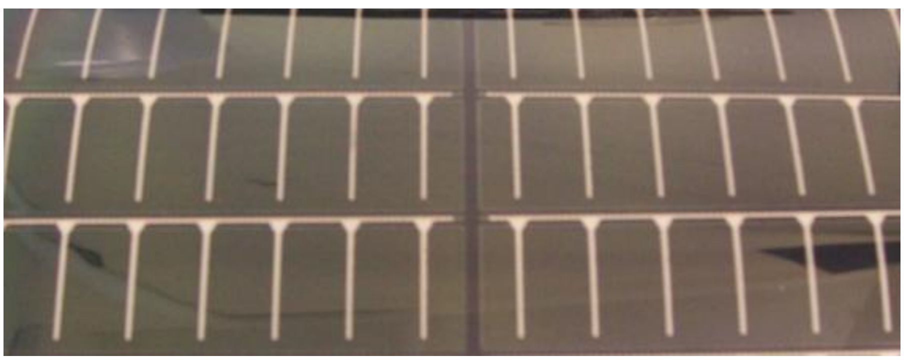

Figure 3: Amorphous silicon thin-film/flexible solar panel purchased from Silicon Solar Inc., Centennial, CO

Water quality was first measured from new thin film solar panels, and then measured after undergoing an accelerated aging/weathering process. To investigate how weathering and damaging of silicon solar cells impact the runoff water quality, accelerated aging of the thin film cells was carried out through two processes: ultraviolet (UV) treatment and heat treatment. Dry heat at 85^{o}C 1000 hours is equivalent to 20 years of weathering (Otth and Ross, 1983).

Equivalent outdoor UV exposure can be calculated as

$$Eq\,Yrs\,of UV Exp = \frac{Irradiance\;\left(\frac{W}{m^2}\right) \times Exposure\,Time\;(s)}{Annual\,UV\,Dosage\;\left(\frac{J}{m^2}\right)}$$

where average annual UV dosage is about 330MJ/m^2/year; average daily irradiance for hot and dry climates is 0.9131MJ/m^2/day, hot and humid climates is 0.7666MJ/m^2/day, and cool and mild climates is 0.9117MJ/m^2/day (Kennedy and Terwilliger, 2005). Furthermore, according to American Society of Testing Materials (ASTM) Standard G15, used for accelerated weathering of materials, a maximum of 2000MJ/m^2 for wavelengths under 400 nm is equal to 6 years of outdoor exposure.

After accelerating aging/weathering, these solar panels will be tested again to see how aging affects the water quality of harvested rainwater. These results have not been finalized and will not be presented in this report. Future experiments planned for this research also include actual outdoor exposure or weathering of the solar panels over a period of a period of months or years.

Principal Findings

Water quality of the harvested synthetic rainwater from new amorphous silicon thin-film/flexible solar panels and USEPA drinking water standards are summarized in Table 2.

Table 2: Water quality of harvested synthetic rainwater from new Si thin film cell compared to USEPA drinking water standards

	Synthetic Rainwater	***New Si Thin-Film/Flexible Cell***	***USEPA Drinking Water Standards***
pH	6.53	5.16	6.5 - 8.5
Turbidity (NTU)	0	1.5	<1
TSS (mg/L)	0	1.07	5*
Nitrate (mg-N/L)	Above Detection Limit of 30mg/L	25.15	10
Nitrite (mg-N/L)	$5.75x10^{-2}$	$1.307x10^{-2}$	1

*USEPA non-potable urban water reuse guideline

These results indicate water quality measurements for the harvested rainwater did not exceed USEPA drinking water standards except for turbidity and nitrate. However, nitrate and nitrite concentrations found from the harvested rainwater are most likely from the synthetic rainwater. Furthermore, these results do not account for a first-flush system, which diverts an initial surface runoff that is not collected for usage. Mendez et al. (2011) found that after the first-flush, the harvested rainwater met the USEPA MCL for nitrate. Therefore, in a real system, high concentrations of nitrate may be avoided by using a first-flush system.

The pH is lowered from 6.53 to 5.16, indicating that compounds, such as metals, which generally lower the pH, may have leached from the solar panel into the harvested rainwater. Nonetheless, it is important to note there that the USEPA drinking water standards are only used here as a basis of comparison, however, rainwater consumers do not have to meet these regulations depending on the end use of the rainwater.

Turbidity exceeded the USEPA drinking water standard for filtration systems; however the samples did not exceed USEPA non-potable urban water reuse guidelines, which states that the average turbidity over a 24 hour period should be less than or equal to 2 NTU and turbidity should not exceed 5 NTU at any time. These results indicate that proper treatment, such as filtration, is needed for this harvested rainwater from a newly installed thin film solar panel to be used as a potable water resource.

Table 3 presents the metals leached from the new amorphous silicon thin-film/flexible solar panel after this 24 hour re-circulation of rainwater. The metal concentrations found in the rainwater harvested from flexible solar panels were obtained by subtracting the measured concentrations in these samples with the baseline concentrations from the synthetic rainwater. These results are compared to available USEPA drinking water maximum contaminant levels (MCL) of certain metals.

Table 3: Metals leached into synthetic rainwater from new Si thin film cell compared to USEPA drinking water MCL

Metal	Concentration in Synthetic Rainwater (mg/L)	Concentration found in Rainwater Harvested from Thin-Film/Flexible Solar Panel (mg/L)	USEPA Drinking Water MCL (mg/L)
Chromium (Cr)	0	0.001	0.1
Aluminum (Al)	0.00033	0.014	0.05 to 0.2*
Manganese (Mn)	0.00042	0.0029	0.05*
Iron (Fe)	0.00013	0.03	0.3*
Copper (Cu)	0.00017	0.15	1.3
Zinc (Zn)	0.0016	0.056	5.0
Arsenic (As)	0.0000028	0.00013	0.01
Selenium (Se)	0.0000029	0.00025	0.05
Silver (Ag)	0.000046	0.0056	0.10*
Cadmium (Cd)	0.0000013	0.0003	0.0005
Antimony (Sb)	0.000014	0.00037	0.006

Barium (Ba)	0.000025	0.0042	2.0
Thallium (Tl)	0	0.000052	0.002
Lead (Pb)	0.00010	0.029	0.015
Uranium (U)	2.3×10^{-8}	0.0000036	0.03

*USEPA secondary drinking water standards

These results indicate that the majority of the metals that leached from the newly installed thin film solar panel did not exceed USEPA drinking water MCLs. However, lead did exceed the USEPA MCL. Potential health risks of lead in drinking water are delays in physical or mental development in infants and children, and kidney problems and high blood pressure in adults. Moreover, unlike the other metals, which are orders of magnitude less than their corresponding MCL, cadmium is present at 0.0003mg/L, which is close to the MCL of 0.0005mg/L. Therefore, cadmium, a heavy metal that causes kidney damage, should be closely monitored in subsequent experiments.

The re-circulation system of rainwater used for these experiments does not necessarily represent a real rainstorm. This lab-scale set-up only allows us to understand what water quality parameters might be affected by solar panels, but does not necessarily provide accurate concentrations of leached contaminants into rainwater. The impacts on these water quality indicators will need to be studied in more detail under more realistic conditions. It is also important to note that these results are from a newly installed solar panel. Higher concentrations of leached metals may occur as the solar panel is weathered and ages with time. The solar panels currently are in the aging process using heat treatment, and results are pending.

Table 4 presents the metals leached from the new amorphous silicon thin-film/flexible solar panel after this 24 hour re-circulation of rainwater. These results are compared to available recommended metal limits found in USEPA water reuse guidelines for non-potable uses.

Table 4: Metals leached into synthetic rainwater from new Si thin film cell compared to USEPA water reuse guidelines for non-potable uses

		USEPA Water Reuse Limits	
Metal	***Thin Film (mg/L)***	***Long-Term Use (mg/L)***	***Short-Term Use (mg/L)***
Aluminum (Al)	0.014	5.0	20
Arsenic (As)	0.00013	0.10	2.0
Boron (B)	0.14	0.75	2.0
Cadmium (Cd)	0.00030	0.01	0.05
Cobalt (Co)	0.0018	0.05	5.0
Chromium (Cr)	0.0010	0.10	1.0
Copper (Cu)	0.15	0.20	5.0
Iron (Fe)	0.030	5.0	20
Manganese (Mn)	0.0029	0.20	10
Molybdenum (Mo)	0.0019	0.01	0.05
Nickel (Ni)	0.016	0.20	2.0
Lead (Pb)	0.029	5.0	10
Selenium (Se)	0.00025	0.02	0.02
Vanadium (V)	0.00018	0.10	1.00
Zinc (Zn)	0.056	2.00	10.00

These results show that none of the metals that leached from the newly installed thin film solar panel exceeded USEPA recommended limits for non-potable water reuse, in either cases of long-term or short-term usage. Therefore, rainwater can be harvested from solar panels for non-potable uses, such as irrigation. However, once again, it is important to note here that these results are obtained from a newly installed solar panel. Higher concentrations of leached metals may occur as the solar panel is weathered and ages with time. Figure 4 shows a flexible solar panel that underwent about 3 weeks of accelerated heat treatment, which is equivalent to approximately 10 years of weathering in dry climate. The polymer packaging appears to be deteriorated.

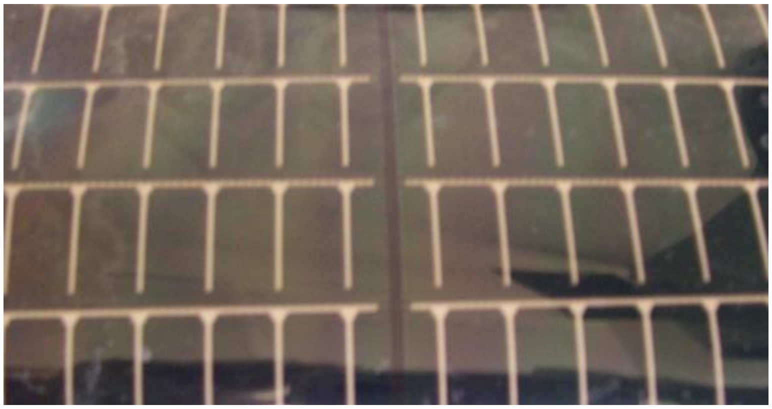

Figure 4: Accelerated weathered/aged amorphous silicon thin-film/flexible solar panel after 3 weeks of heat treatment

Results from these aged solar panel studies have not been finalized and will not be presented in this report. Our hypothesis is these metal concentrations will increase as more metals can be potential leached off the solar panels, as the protective covering of the thin-film begins to deteriorate with age.

Significance

The significance of this project is solar panels installed on rooftops can become a source of metal contaminants for rainwater harvesting systems installed in the same residential household. Results indicate that harvested rainwater from a newly installed amorphous silicon thin film solar panel suggest that the concentrations of cadmium and lead might be elevated for potable uses. Nonetheless, these water quality indicators of harvested rainwater from a solar panel may change as the solar panel undergoes weathering and aging. Further work is needed to fully understand how solar panels can impact the water quality of harvested rainwater from rooftops.

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