ACKNOWLEDGMENTS

The authors would like to thank the two anonymous reviewers for their insightful and constructive comments that improved the quality of our work as well as the Ministry of Economic Affairs and Climate Policy of the Netherlands for its financial support enabling the research behind this publication.

AUTHOR CONTRIBUTIONS

B.S. and B.v.d.Z. designed the study; B.S., R.J.D., and B.v.d.Z. drafted the article; B.S. gathered the data and generated the figures; B.S., R.J.D., and B.v.d.Z. analyzed the data and discussed the results; B.S. and B.v.d.Z. produced the final manuscript.

1. Dutton, J.M., and Thomas, A. (1984). Treating Progress Functions as a Managerial Opportunity. AMR *9*, 235–247.
2. Jaber, M.Y. (2017). Learning Curves Theory, Models, and Applications (CRC Press).
3. International Energy Agency (2000). Experience curves for energy technology policy.
4. Weiss, M., Junginger, M., Patel, M.K., and Blok, K. (2010). A review of experience curve analyses for energy demand technologies. Technol. Forecast. Soc. Change *77*, 411–428.
5. Rubin, E.S., Azevedo, I.M.L., Jaramillo, P., and Yeh, S. (2015). A review of learning rates for electricity supply technologies. Energy Policy *86*, 198–218.
6. McDonald, A., and Schrattenholzer, L. (2001). Learning rates for energy technologies. Energy Policy *29*, 255–261.
7. Schmidt, O., Hawkes, A., Gambhir, A., and Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. Nat. Energy *2*, 17110.
8. Ferioli, F., Schoots, K., and van der Zwaan, B.C.C. (2009). Use and limitations of learning curves for energy technology policy: A component-learning hypothesis. Energy Policy *37*, 2525–2535.
9. Rivera-Tinoco, R., Schoots, K., and van der Zwaan, B. (2012). Learning curves for solid oxide fuel cells. Energy Convers. Manage. *57*, 86–96.
10. Nemet, G.F. (2006). Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy *34*, 3218–3232.
11. Yeh, S., and Rubin, E.S. (2012). A review of uncertainties in technology experience curves. Energy Econ. *34*, 762–771.
12. Dahlgren, E., Göçmen, C., Lackner, K., and van Ryzin, G. (2013). Small Modular Infrastructure. Eng. Econ. *58*, 231–264.
13. Sinclair, G., Klepper, S., and Cohen, W. (2000). What's Experience Got to Do With It? Sources of Cost Reduction in a Large Specialty Chemicals Producer. Manage. Sci. *46*, 28–45.

[1]TNO, Energy Transition department, Amsterdam, the Netherlands

[2]University of Amsterdam, Faculty of Science (HIMS and IAS), Amsterdam, the Netherlands

[3]Johns Hopkins University, School of Advanced International Studies (SAIS), Bologna, Italy

*Correspondence: bob.vanderzwaan@tno.nl

https://doi.org/10.1016/j.joule.2020.03.010

Commentary

Assessing the Regulatory Requirements of Lead-Based Perovskite Photovoltaics

Nicole Moody,[1]
Samuel Sesena,[1]
Dane W. deQuilettes,[2]
Benjia Dak Dou,[2]
Richard Swartwout,[3]
Joseph T. Buchman,[4]
Anna Johnson,[1]
Udochukwu Eze,[1]
Roberto Brenes,[2,3]
Matthew Johnston,[3]
Christy L. Haynes,[4]
Vladimir Bulović,[2,3]
and Moungi G. Bawendi[1,*]

Nicole Moody, Samuel Sesena, Dane W. deQuilettes, Benjia Dak Dou, Richard Swartwout, Anna Johnson, Udochukwu Eze, Roberto Brenes, Matthew Johnston, Vladimir Bulović, and Moungi G. Bawendi are members of Tata-MIT GridEdge Solar, an interdisciplinary research program at the Massachusetts Institute of Technology working toward scalable design and manufacturing of lightweight, flexible solar cells.

Joseph T. Buchman and Christy L. Haynes are part of the Center for Sustainable Nanotechnology, a multi-institutional partnership aimed at understanding the fundamental chemical and physical processes that govern the transformations and interactions of nanoparticles in the environment.

Metal halide perovskite photovoltaic (PV) devices offer promising performance and unique applications, with demonstrated power conversion efficiencies that exceed 20%, stable operation over thousands of hours, and compatibility with flexible substrates.[1] However, the highest-performing perovskite materials for PV applications contain lead, which is regulated worldwide as a hazardous material.[2–4]

As several companies and research labs are considering the possibility of large-scale deployment of lead-based perovskite PV modules,[1] the topic of regulatory compliance is now critical but has been largely overlooked. Here, we present a preliminary evaluation of lead halide perovskite (LHP) PVs according to the European Union (EU) Restriction of Hazardous Substances (RoHS) Directive[2] and United States Resource Conservation and Recovery Act (RCRA) lead regulations.[3] The RoHS Directive and RCRA both aim to reduce the risk of harm caused by hazardous materials and are legal regulatory frameworks that all commercial PVs are subject to (i.e., Si and CdTe). By characterizing the lead concentration and lead leaching behavior of perovskite films on glass and flexible substrates using RoHS Directive and RCRA mandated protocols, we find that some of the key advantages of lead-based perovskites as a solar technology, specifically their potential for high specific power (W g^{-1}) as well as lightweight and portable applications, are at odds with the regulatory frameworks currently in place due to international processing of waste on a

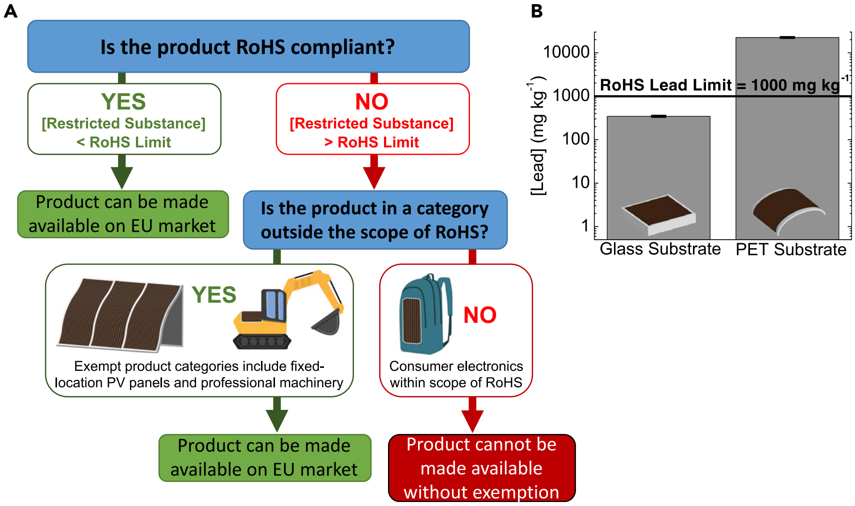

Figure 1. Evaluation of Restriction of Hazardous Substances Directive Regulation on Perovskite PVs

(A) Schematic of RoHS Directive regulatory framework.

(B) Total lead concentration by weight of 1″ × 1″ perovskite thin films on glass and polyethylene terephthalate (PET) substrates. Data are represented as mean ± SD. See also Table S1.

per-weight basis.[5] We further perform a risk assessment of a worst-case, end-of-life-disposal scenario for LHP PVs into an unlined landfill to determine whether lead solubility or total lead content poses a greater risk for public lead exposure under catastrophic failure. We conclude from our regulatory analysis that that substrate weight plays a substantial role in the regulation of LHP PVs by affecting the lead concentration by weight, which could lead to additional regulatory obstacles for commercial deployment of lightweight, flexible perovskite PV modules.

Restriction of Hazardous Substances Directive Regulation

In the EU, the RoHS Directive is the primary regulation that prevents the distribution of potentially hazardous commercial electrical and electronic equipment (EEE).[2] Its direct impact on the market is evident by up to 94% reductions in the lead content of a variety of consumer electronics in the EU,[6] as well as the adoption of similar policies in China, South Korea, and Japan.[7] The RoHS Directive requires that the concentration of restricted hazardous substances in EEE be evaluated on a per-weight basis, where the maximum tolerated weight concentration for lead in homogeneous materials according to the RoHS Directive is 0.1%, or 1,000 mg of lead per kg of total material.[2] Importantly, the flow chart in Figure 1A shows that all EEE must comply with this weight concentration limit or receive an exemption in order to be made available on the EU market.[2] For example, when applied to CdTe PVs, the cadmium concentration by weight in the PVs exceeds RoHS limits.[7] However, fixed-location PV modules are a product category excluded from the RoHS Directive, so fixed-location CdTe PV modules can be placed on the EU consumer market.[2,7] We highlight that although other common metrics for PVs (i.e., $ [USD] m^{-2}) are determined on a per-area basis, regulation of waste is performed on a per-weight basis because bulk waste, including recycling, is processed, tracked, and priced on the basis of weight.[5]

Following the standard RoHS Directive procedure applied to other PVs, we measure the total lead concentration of a perovskite film on a glass substrate compared to a flexible, thin polyethylene terephthalate (PET) substrate. Both films have the same surface area, thickness, and perovskite composition. We have chosen to ignore the other device transport layers, as they have a minimal effect on overall device weight compared to the substrate (Table S3). We also omit encapsulation layers and analyze the perovskite film and substrate together as homogeneous materials as previously done for portable copper indium gallium selenide (CIGS) PVs.[8]

In order to determine the total lead concentration, we perform microwave digestion to dissolve the lead and then analyze the lead concentration of the resulting solution with inductively coupled plasma optical emission spectrometry (ICP-OES). Figure 1B and Table S1 show a measured total lead concentration of 344 ± 4 mg kg^{-1} for a perovskite thin film on glass versus 22,400 ± 100 mg kg^{-1} for a film on a PET substrate. Importantly, we observe no statistically significant variation in the total amount of lead ($p = 0.169$) for each of the films and therefore attribute the differences in lead concentration to the substrate weight. As evident in Figure 1B, the film on the lighter PET substrate has a higher lead concentration by weight than the film on the heavier glass substrate, making it less likely to be RoHS compliant when evaluating the perovskite layer and substrate together as a homogeneous material. Although this result appears to have major implications for the commercial viability of flexible perovskite PVs, we will review alternative pathways for commercialization in the discussion section.

Resource Conservation and Recovery Act Regulation

The RoHS Directive does not apply to United States markets,[2] which are instead governed by a different set of regulations. RCRA creates a framework for hazardous waste management in the US.[3] The RoHS Directive primarily

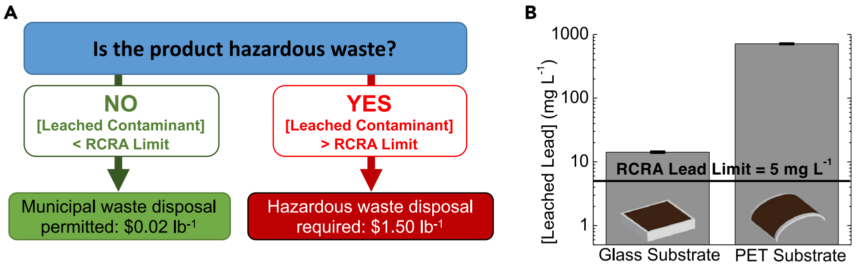

Figure 2. Evaluation of Restriction of Resource Conservation and Recovery Act (RCRA) Regulation on Perovskite PVs

(A) Schematic of RCRA regulatory framework.

(B) TCLP leached lead concentration of 1″ × 1″ perovskite thin films on glass and PET substrates. Data are represented as mean ± SD. See also Table S1.

restricts the distribution of potentially hazardous products based on total content by weight,[2] whereas RCRA regulates the disposal of products and assesses hazardous waste based on leaching potential (Figure 2A).[3] The legally mandated protocol used to determine this leaching potential is the Toxicity Characteristic Leaching Procedure (TCLP), which for solid waste involves the following (see Supplemental Information for detailed experimental procedure): (1) product destruction to yield a particle size reduction of solid waste to < 1 cm, (2) extraction with end-over-end agitation in a 20:1 ratio by weight of extraction fluid to solids for 18 ± 2 h, (3) filtration of the extraction mixture through a 0.6 to 0.8 μm glass fiber filter to remove solids, and (4) chemical analysis with appropriate analytical methods to determine the concentration of the analytes.[3]

Similar to RoHS, RCRA incorporates the per-weight basis for waste processing through the addition of an acidic extraction fluid to the sample in a fixed ratio by weight.[3] The extraction fluid for non-alkaline solid waste is an acetic acid buffer meant to simulate landfill conditions.[3,9] We perform the TCLP on two perovskite films on glass and PET substrates and measure the leached lead concentrations to be 14.2 ± 0.2 and 713 ± 5 mg L^{-1}, respectively (Figure 2B; Table S1). Indeed, this result makes sense in the context of a fixed mass of waste in a landfill with a fixed amount of acetic acid, where a high mass substrate will reduce the concentration of lead in comparison to a low-mass substrate.

The perovskite films on both glass and PET substrates exceed the 5 mg L^{-1} lead limit from the TCLP and thus require hazardous waste disposal rather than landfilling.[3,4] Importantly, this hazardous waste disposal requirement could add significant costs to the life cycle of perovskite PVs, as hazardous waste disposal costs $1.50 lb^{-1} ($3.31 kg^{-1}) on average across waste management methods compared to $0.02 lb^{-1} ($0.04 kg^{-1}) for non-hazardous waste.[10] We note, however, that such waste disposal costs can be mitigated by recovering and recycling perovskite PV modules.

Risk Assessment of Flexible Perovskite Modules

Both the EU RoHS Directive and US RCRA aim to reduce the risk of harm caused by hazardous materials in waste, but they characterize this risk using different criteria: total concentration in the case of the RoHS Directive and leached concentration in the case of RCRA.[2,3] We thus determine whether total or leached lead poses a greater risk to human and environmental health and safety with the goal to determine the best strategies to mitigate the potential negative impacts of LHP PVs. Landfill disposal offers an advantageous testbed for such risk analysis, as it presents a large concentration of perovskite PVs that have undergone significant destruction, are not well shielded from the surrounding environment, and could impact the general public rather than a smaller subset of the population such as recycling facility workers.

The U.S. Environmental Protection Agency's (EPA's) Delisting Risk Assessment Software (DRAS) can be used to conservatively estimate exposure point concentrations for various media following the disposal of waste containing hazardous material in an unlined landfill.[11] Soil, air, and surface water concentrations are determined by the *total concentration* of hazardous material by weight in the waste, as exposure results from *physical* erosion and transport of the hazardous material, while the groundwater concentration is determined by the *leached (TCLP) concentration*, as exposure results from *chemical* leaching of the hazardous material from the landfill into a downgradient well (Figure 3A).[11] The determination of DRAS exposure point concentrations can thus be thought of as a preliminary screen to determine which aspect of LHP PVs poses a greater risk to human and environmental health: the total lead content or the lead leaching potential.

In order to estimate a worst-case scenario of perovskite landfill disposal, we calculate the air, soil, groundwater (Figure 3C), and surface water (Figure S2) lead concentrations resulting from the landfilling of a hypothetical 5 megawatt-peak (MW_p) solar plant with flexible LHP modules (Figure 3B) (see Supplemental Information for calculation details). We observe that the contamination levels for air, soil, and surface water are several orders of magnitude below the maximum acceptable risk levels, but the lead concentration in groundwater is less than a factor of 4 below the EPA drinking water lead limit for the landfilled modules.[11] Therefore,

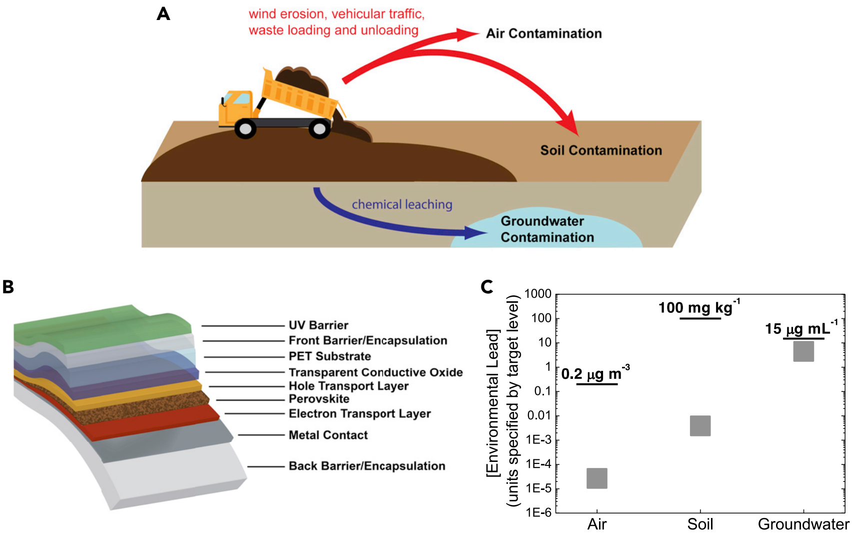

Figure 3. Lead Contamination from Landfilled Perovskite Modules

(A) Schematic illustration of contamination pathways resulting from disposal in an unlined landfill.[11]

(B) Schematic illustration of a PET perovskite module architecture.

(C) Estimated lead exposure point concentrations resulting from landfilling a hypothetical 5 MW_p perovskite solar project for air, soil, and groundwater media (gray squares) relative to U.S. Environmental Protection Agency target levels for acceptable risk (black lines).[11]

we conclude that groundwater has the highest potential to exceed maximum acceptable risk levels for lead contamination, and thus the lead leaching potential of perovskite PVs is a greater source of risk than the lead content in this landfill disposal scenario.

Discussion: Market Implications and Risk-Reduction Strategies

For EU markets, although our preliminary evaluation shows that flexible perovskite PVs may not be RoHS compliant, their deployment may still be possible with exemptions, as shown in Figure 1. Fixed-location PV panel installations are currently a RoHS-exempt product category in the EU,[2] so professionally installed, fixed-location perovskite solar panels could still be commercially feasible. However, portable applications that take advantage of the lightweight and flexible form factors of perovskite PVs would likely need to be granted additional exemptions, especially for non-professional use, making their widespread commercial deployment more challenging under the RoHS Directive regulatory framework. We highlight that exemptions may be granted for products that provide compelling evidence of socioeconomic advantages, but such exemptions are temporary in order to achieve the gradual removal of hazardous substances.[2]

For US markets, flexible LHP PVs are more likely to be characterized as hazardous waste compared to rigid modules, because their higher lead content by weight leads to high TCLP leached lead concentrations. Reducing such lead leaching is critical, as our DRAS analysis reveals that leached lead is a greater public and environmental health risk than total lead content for landfilled LHP PVs. In order to quantify the amount of leached lead, we have found that the TCLP method provided by RCRA serves as a reliable and generally accessible technique that also reflects the legally required evaluation of hazardous waste.[3] In comparison to other techniques,[12] the TCLP has a greater potential for lead extraction[9] (Figure S3), requires a greater degree of sample destruction,[3,12] and can be applied to a wide range of perovskite architectures (Figure S4). TCLP experiments could thus provide more comprehensive information about the chemical capability of perovskite encapsulation architectures at preventing the leaching of hazardous materials rather than just the mechanical strength.[9,12]

Conclusions

According to the EU RoHS Directive and US RCRA legal regulatory frameworks, our analysis shows that substrate weight plays a substantial role in the regulation of LHP PVs. Specifically, substrate choice leads to order-of-magnitude differences in the lead concentration by weight, a key factor in the determination of regulatory compliance. Importantly, we find that lead leaching of perovskite PVs poses greater risk to human and environmental health compared to the total lead content itself. With companies and research labs both focusing on testing larger area perovskite devices and modules in the field,[1] we believe that increased focus should be placed on reducing lead leakage from perovskite modules.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2020.03.018.

ACKNOWLEDGMENTS

Funding was provided in part by the Tata Trusts through the Tata-MIT GridEdge Solar research program. Experimental work performed by J.T.B. was supported in part by the National Science Foundation under the Center for Sustainable Nanotechnology (CSN), CHE-1503408. The CSN is part of the Centers for Chemical Innovation Program. J.T.B. also acknowledges support by a National Science Foundation Graduate Research Fellowship (grant number 00039202). R.B. acknowledges support by a National Science

Foundation Graduate Research Fellowship (grant number 1122374).

AUTHOR CONTRIBUTIONS

Conceptualization, N.M.; Methodology, N.M.; Software, S.S.; Validation, N.M.; Investigation, N.M., S.S., D.W.D., J.T.B., A.J., and U.E.; Resources, N.M., J.T.B., B.D.D., R.S., R.B., and M.J.; Writing – Original Draft, N.M.; Writing – Review & Editing, N.M., S.S., D.W.D., J.T.B., A.J., U.E., B.D.D., R.S., R.B., M.J., C.L.H., V.B., and M.G.B.; Project Administration, N.M. and M.G.B.

DECLARATION OF INTERESTS

V.B. is an advisor to Swift Solar, a US company developing perovskite photovoltaics, and is the co-founder of Ubiquitous Energy, a US company developing visibly transparent photovoltaics.

1. Kim, D.H., Whitaker, J.B., Li, Z., van Hest, M.F.A.M., and Zhu, K. (2018). Outlook and Challenges of Perovskite Solar Cells toward Terawatt-Scale Photovoltaic Module Technology. Joule *2*, 1437–1451.
2. European Parliament and Council of the European Union (2011). 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. Off. J. Eur. Union *174*, 88–110. http://data.europa.eu/eli/dir/2011/65/oj.
3. Environmental Protection Agency (1990). Hazardous Waste Management System; Identification and Listing of Hazardous Waste. Toxicity Characteristics Revisions. Fed. Reg. *55*, 26986–26998. https://www.epa.gov/sites/production/files/2016-04/documents/55fr26986.pdf.
4. Toxicity Characteristic. (2011). (40 C.F.R § 261.24).
5. Knight, W.A., and Sodhi, M. (2000). Design for Bulk Recycling: Analysis of Materials Separation. CIRP Annals. *49*, 83–86.
6. Bogaert, S., van Acoleyen, M., van Tomme, I., De Smet, L., Fleet, D., and Salado, R. (2008). Study on RoHS and WEEE Directives. European Commission DG Enterprise and Industry 1–320.
7. Sinha, P., Kriegner, C.J., Schew, W.A., Kaczmar, S.W., Traister, M., and Wilson, D.J. (2008). Regulatory policy governing cadmium-telluride photovoltaics: A case study contrasting life cycle management with the precautionary principle. Energy Policy *36*, 381–387.
8. SGS-CTSC Standards Technical Services (Shanghai) Co (2015). Verification Report No. SHAEC1503205801. Portable Solar Charger SP15-00542 1–15.
9. United States Environmental Protection Agency (1999). Public Meeting on Waste Leaching. Proceedings of the Environmental Protection Agency 1–44.
10. Davey, K., and Hummel, N. (2017). P2 Cost Calculator (Environmental Protection Agency). https://www.epa.gov/sites/production/files/2017-06/p2_cost_calculator_apr-13-2017.xlsm.
11. (2008). United States Environmental Protection Agency Office of Solid Waste (RCRA Delisting Technical Support Document).
12. Jiang, Y., Qiu, L., Juarez-Perez, E.J., Ono, L.K., Hu, Z., Liu, Z., Wu, Z., Meng, L., Wang, Q., and Qi, Y. (2019). Reduction of lead leakage from damaged lead halide perovskite solar modules using self-healing polymer-based encapsulation. Nat. Energy *4*, 585–593.

[1]Department of Chemistry, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge,
MA 02139, USA

[2]Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

[3]Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

[4]Department of Chemistry, University of Minnesota, 207 Pleasant St SE, Minneapolis, MN 55455, USA

*Correspondence: mgb@mit.edu

https://doi.org/10.1016/j.joule.2020.03.018